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ELECTRICAL ENGINEERING

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**CONDITION MONITORING OF POWER TRANSFORMER AS PART OF
POWER PLANT MAINTENANCE PROCESS**

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SYMBOLS AND ABBREVIATIONS

ppm	Parts per million
ABB	Asea Brown Boveri
CBM	Condition based maintenance
CIGRE	International Council on Large Electric Systems
DGA	Dissolver Gas Analysis
EMI	Electromagnetic interference
EN	European Norm
EPRI	Electric Power Research Institute
HMI	Human machine interface
HV	High voltage
HVDC	High-voltage direct current
GSU	Generator step-up
IEC	International Electrotechnical Commission
IED	Intelligent electronic device
IEEE	Institute of Electrical and Electronics Engineers
IMIA	International Association of Engineering Insurers
LV	Low voltage
NCC	Network control center
OLTC	On load tap changer
ONAF	Oil Natural and Air Forced
OPC	Open connectivity via open standards
OSA-CBM	Open Systems Architecture for Condition-Based Maintenance
OSA-EAI	Open System Architecture for Enterprise Application Integration
PD	Partial discharge
PLC	Programmable logic controller
RAM	Requirement Abstraction Model
RCM	Reliability Centered Maintenance
RTD	Resistance temperature detector

SCADA	Supervisory Control And Data Acquisition
SCL	Substation Configuration Description Language
TW	Tertiary winding
UHF	Ultra High Frequency
US	United States of America
VFT	Very Fast Transient

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TIIVISTELMÄ

Päämuuntaja on yksi kriittisimmistä sähköverkon pääkomponenteista voimalaitoksella, joten myös sen käyttövarmuus on tärkeässä osassa. Tällä hetkellä muuntajan käytönaikaiseen kunnonvalvontaan ei käytetä merkittävästi resursseja loppukäyttäjien osalta, mutta huollot tehdään pääsääntöisesti valmistajien ohjeiden mukaisesti ja siten huolehditaan päämuuntajan käyttövarmuudesta. Muuntajat ovat normaalisti pitkäikäisiä ja varmatoimisia komponentteja, joten käytönaikainen kunnonvalvonta ei ole saanut paljoakaan huomiota voimalaitoksissa. Kuitenkin kustannukset vaurioitumisesta voivat olla erittäin suuria ja siten valvonta on perusteltua.

Tämä diplomityö keskittyy päämuuntajan käytönaikaiseen kunnonvalvontaan. Tavoitteena on löytää kustannustehokas ja toisiojärjestelmään integroitava ratkaisu, jolla pystytään seuraamaan muuntajan kuntoa riittävällä tasolla. Aihealuetta on tutkittu runsaasti mikä kertoo kasvavasta mielenkiinnosta aiheita kohtaan ja mahdollisista markkinoista tämän tyyppisille palveluille.

Työn alkuosa koostuu kunnossapitoon ja kunnonvalvontaan liittyvien termien määrittelystä. Siinä määritellään myös eri sidosryhmien tavoitteet kunnonvalvonnalle, hyödyntäen delphi-menetelmää. Tämän jälkeen keskitytään päämuuntajan kunnonvalvontaan, joka käsittää päämuuntajan rakenteen, vikaantumistilastot, kunnonvalvontamenetelmät sekä kunnonvalvonnassa käytettäviä mittalaitteita. Lisäksi kunnonvalvonnan mahdollisia kehityssuuntia käsitellään lyhyesti.

Työn tulokset jakautuvat karkeasti kahteen osaan. Ensiksi määritellään vaatimukset muuntajan käytönaikaiselle kunnonvalvonnalle kolmella eri tasolla. Toiseksi määritellään käytönaikaisen kunnonvalvonnan ratkaisuehdotus testiprojektia varten, jonka tavoitteena on kerätä kokemuksia muuntajan kunnonvalvonnasta sekä käytettävistä mittalaitteista.

AVAINSANAT: voimalaitos, päämuuntaja, kunnonvalvonta, kunnossapito

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ABSTRACT

Power transformer is one of the most critical components for electrical network in power plants. This means that dependability has a big role. At the moment end users allocate resources to power transformer maintenance. Resources for on-line condition monitoring on the other hand are not very significant. Reason for this is that transformers are reliable and long life components. However, failure costs might be very significant and online monitoring is justified from that point of view.

This thesis focuses on power transformer online condition monitoring. The goal is to find cost-effective and integrated solution which provides good-enough transformer monitoring. The subject has been studied quite a lot which tells about increasing interest towards the subject and might indicate possible markets for transformer monitoring services.

In the beginning research will focus on describing maintenance and condition monitoring related terms. Also goals are defined for different stakeholders applying the Delphi method. The middle part of the work focus on power transformer structure, fault statistics, condition monitoring methods and measurement devices. Also possibilities of condition monitoring are covered.

Research results are divided into two different categories. First part of the results will be related to requirements defined for power transformer condition monitoring. Results include requirements for three different ranges of transformer monitoring. Second part of the results contains a specification for pilot project to test power transformer condition monitoring methods and devices.

KEYWORDS: power plant, transformer, condition monitoring, maintenance

1. INTRODUCTION

Maintenance process and maintenance strategies are getting more focus as electric utility companies try to keep their profitability in increasing competition by putting more focus on maintenance actions. One purpose of maintenance is to balance costs and risks in daily operation. For that purpose maintenance needs different tools for correct decision making. These tools can be expert analyses, collected information (maintenance activities, running hours) or condition monitoring which can be done both on-line and off-line. This thesis is focused on automated on-line monitoring methods.

Power transformer is one of the most critical electrical network components in power plants. At the moment end users allocate resources for power transformer maintenance and it is on an acceptable level. Resources for on-line condition monitoring on the other hand are not very significant, despite that subject has been studied quite a lot and even very complex monitoring systems are available. Subject of the thesis is based on cooperation between ABB Distribution Automation and Wärtsilä Finland Oy. The main target is to develop condition monitoring system for main electrical components in Wärtsilä power plants. In the first phase of the project the target is to build condition monitoring for power transformer and this is also the subject of this research. In practice this means providing condition monitoring system under certain limitations set by different stakeholders. Interest towards the subject has grown lately and this could also mean possible markets for this kind of service.

Based on the statistics, the amount of transformer failures is not huge but economic losses are however significant (Bartley 2003). Even these statistics provide enough information to motivate to find a solution for transformer condition monitoring to avoid outages, especially for generator step-up transformers. This research should also take into account costs of the system. Cargol (2005: 1) claims in his article that most utilities are willing to spend up to 5 % of the cost of a transformer on monitoring equipment.

1.1. Stakeholders

Condition monitoring system is one part of a complex system in power plants. This system is affected by several different stakeholders and those may vary from system providers to plant owners. Following sections introduces most important stakeholders from condition monitoring point of view.

1.1.1. Condition monitoring system provider

First link in the chain is monitoring system provider. Their task is to design and to produce transformer condition monitoring system. Usually these companies are focused on automation technology where condition monitoring products can be one area of expertise. Automation focused companies normally have good connections to primary equipment manufacturers. Also measurement sensor manufacturers can be included in this group.

As an example ABB Distribution Automation is a business unit of the ABB group that has specialized in developing protection relays and feeder terminals for distribution networks. Condition monitoring is not their primary business but secondary system systems in substations are familiar.

1.1.2. Power plant manufacturer and service provider

Power plant manufacturer and service provider is usually a company which provides power sources for power generation. In most cases these companies also provide turnkey solutions for complete power plants. It is also common that these companies provide service solutions for the end users. These services can include spare part deliveries or providing maintenance process. Their role in condition monitoring is to use this tool when providing maintenance services.

Wärtsilä Finland Oy is both a Ship Power Supplier for all types of marine and offshore applications and a provider of power plants in the decentralized energy market. The

global service network provides service, maintenance and reconditioning solutions both for machinery and power plants throughout the lifetime of the installations.

1.1.3. Electric utility

An electric utility is a company that engages in the generation, transmission, and distribution of electricity for sale. In most countries electric utility covers either transmission or distribution business. Often electric utilities have generation business. The electrical utility industry is a major provider of energy in most countries. Electric utilities include investor owned, publicly owned and nationalized entities.

Electric utility is usually the end user and owner of the power plant. They define the requirements for condition monitoring through maintenance strategies. Electric utilities role with condition monitoring depends if they have outsourced maintenance activities or not. Their interface is usually through maintenance where on-line condition monitoring can be one tool. Although, utilities may be interested about measurement and health data gathered from their equipment, even if they have outsourced maintenance activities.

1.2. Structure and expectations

Hypothesis for the research is that power transformer condition monitoring can be achieved on a good enough level with equipment that is already on the market. Condition monitoring system is designed for power plant environment so it means that monitoring system is used with generator step-up transformers. Output from the system should be detection of evolving faults. Diagnostics or prognostics are not necessary for the system at this point.

Topic will be limited to power transformers and to the size which is usual for diesel-engine power plants. Condition monitoring in this case covers measurement, data processing and storing. Thesis will not cover how the information is handled in or

transferred to high-level systems, like Supervisory Control And Data Acquisition (SCADA) systems.

Sub problems for the hypothesis are the parts which compile the research problem and these are:

- Needed and relevant parameters to define condition of a power transformer
- Measurement devices for condition monitoring
- Requirements for monitoring system

Structure of the thesis is based on details above. Second chapter of the thesis defines all the main terms related to maintenance and condition monitoring. Third chapter studies goals of condition monitoring for different stakeholders and compare these to the goals defined in the literature. Fourth chapter will concentrate on structure and aging of transformer. This chapter also includes possible faults and different on-line monitoring methods. Fourth chapter also introduces some measurement devices. Fifth chapter will introduce possibilities of transformer condition monitoring. Sixth chapter starts the initial planning of transformer condition monitoring system. Basically it will introduce limiting factors and requirements in general level. Seventh chapter introduces the technical specification for the transformer condition monitoring system from pilot project point of view.

Following results can be expected from this thesis. First part of the results is related to requirements and definition of condition monitoring systems. Second part of the results is a specification for transformer condition monitoring pilot project. The goal is that the results could be used in condition monitoring projects.

2. CONDITION MONITORING RELATED DEFINITIONS

Terms are defined in many different standards. This also gives problems to decide which definitions to use as there are plenty of differences between different standards. This chapter will define the terms used in this thesis and will not concentrate on the problem of several different definitions of terms.

2.1. Dependability

According to IEC 60300-1 dependability is a combining term used to describe the availability performance and its influencing factors. These factors are reliability performance, maintainability performance and maintenance support performance. Relations between different terms and influencing factors are shown in Figure 1.

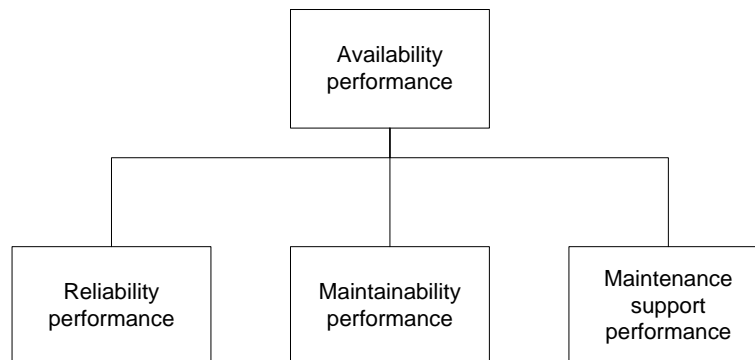


Figure 1. Dependability relationships (IEC 60300-1).

IEC 60300-1 also defines the dependability related factors. The definitions are following:

“Availability performance is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.

Reliability performance is the ability of an item to perform a required function under given conditions for a given time interval.

Maintainability performance is the ability of an item under given conditions of use, to be retained in, or restored to a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.

Maintenance support performance is the ability of a maintenance organization, under given conditions, to provide upon demand, the resources required to maintain an item, under a given maintenance policy.”

According to Järviö, Piispa, Parantainen & Åström (2007: 37) condition monitoring is part of the maintainability performance. Maintainability performance is divided into maintainability, repairability and fault observation rate. Condition monitoring is included in fault observation rate.

2.2. Maintenance

Maintenance is combination of all four terms defined in chapter 2.1. This means that condition monitoring is also a part of maintenance.

SS-EN 13306 standard defines maintenance in the following way. “Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.” SS-EN 13306 standard divides maintenance into preventive and corrective maintenance. Preventive maintenance is then divided into condition based and predetermined maintenance. Figure 2 shows the relationships between different terms.

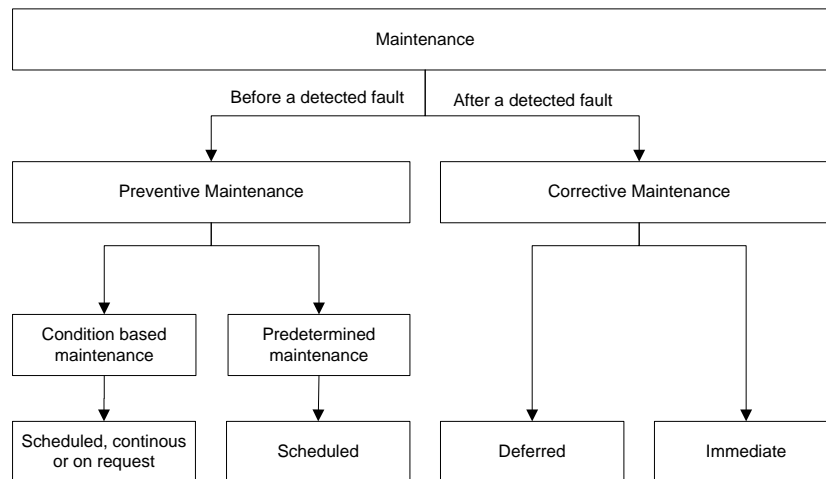


Figure 2. Overview of maintenance (SS-EN 13306).

Corrective maintenance is any maintenance activity which is required to fix a failure that has occurred or is in the process of occurring. This activity may consist of repair, restoration or replacement of components. (Järviö etc. 2007: 49.)

Preventive maintenance is carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item. (SS-EN 13306.)

Pretermimed maintenance is also known as time based maintenance. This is the most traditional way of handling maintenance. It means that running maintenance actions based on manufacturer's service guideline or valid a standard. This method can be slightly modified and this way it is possible to reduce maintenance costs. In practice this means stretching service intervals to longest possible and also only mandatory parts are serviced. (Lee Willis, Welch & Schrieber 2001: 373.) Time based maintenance is a traditional way of handling pretermimed maintenance but it also has some problems. First of all labour costs are high as workload is big. Another problem is that faults between service actions are not noticed.

Condition based maintenance (CBM) is preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. Performance and parameter monitoring may be scheduled, on request or continuous. (SS-EN 13306.)

Based on these definitions it can be clearly seen that we are focusing on condition based maintenance. As additional information predictive maintenance is also defined. This is carried out following a forecast derived from the analysis and evaluation of significant parameters of the degradation of the item (SS-EN 13306).

Reliability centered maintenance (RCM) is also shortly covered in here. Reliability Centered Maintenance analysis provides a structured framework for analyzing the functions and potential failures for a physical asset (such as an airplane, a manufacturing production line, etc.) with a focus on preserving system functions, rather than preserving equipment. RCM is used to develop scheduled maintenance plans that will provide an acceptable level of operability, with an acceptable level of risk, in an efficient and cost-effective manner. (Weibull.com 2009.)

Maintenance process must answer the following seven questions to be called a reliability centered maintenance process:

- What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?
 - In what ways can it fail to fulfill its functions (functional failures)?
 - What causes each functional failure (failure modes)?
 - What happens when each failure occurs (failure effects)?
 - In what way does each failure matter (failure consequences)?
 - What should be done to predict or prevent each failure (proactive tasks and task intervals)?
 - What should be done if a suitable proactive task cannot be found (default actions)?
- (Weibull.com 2009.)

2.3. Condition monitoring

PSK 6201 standard defines condition monitoring in the following way. Condition monitoring determines the actual operating state of an item and assesses its development in order to determine the time of potential failure, service, or repair.

Condition monitoring activities include inspections and monitoring performed either by sensing or by measuring devices, and analysis of measurement results. Condition monitoring provides initial data for planning preventive maintenance and repairs. (PSK 6201.)

This definition does not specify if condition monitoring is done while machine is running or not. This research is referring condition monitoring as automatic condition monitoring done with measurement devices while machine is in operation

2.3.1. Off-line condition monitoring

Off-line condition monitoring takes place during an outage, for maintenance or when an outage has occurred as the result of a transformer or network fault. Off-line monitoring can also include tests. Following parameters can be measured as an example:

- Winding resistances
- Magnetizing currents
- Impedance voltages
- Dielectric loss factor
- Insulation resistance, including core and yoke clamps to earth
- Inter-winding and winding to earth capacitance measurements
- Dielectric response, measurement of moisture in solid insulation (ABB 2004: 124.)

This thesis will not cover off-line condition monitoring methods as the goal is to achieve automated on-line condition monitoring system for power transformer.

2.3.2. On-line condition monitoring

On-line condition monitoring takes place while machine is in operation. On-line monitoring can be divided into manual and automated condition monitoring. This study is especially focusing on automated condition monitoring solutions. On-line condition monitoring is not defined in standards but Electric Power Research Institute (EPRI)

defines on-line condition monitoring as following: “Automated method of monitoring instrument performance and assessing instrument calibration while the plant is in operation and without disturbing the monitored channels.” (EPRI 2004: 2-1.)

Most of automatic monitoring methods are based on manual methods. Good example is dissolved gas analysis. It is traditional way of monitoring transformer oil and it is done manually usually once in a year. Last ten years have brought several devices which automatically take the oil samples and analyze the samples. This allows to take samples more often and to detect faults in much earlier phase. This method is described later in the thesis.

2.3.3. Literature based goals

It can be assumed that one of the primary goals for CBM and condition monitoring is cost saving. According to Järviö (2009) these cost savings can be lower service costs compared to corrective maintenance, unrealized production and indirect costs. Järviö also claims that unplanned service is between four and twelve times more expensive than planned service actions. This research is more interested about the technical aspects which are supportive goals for condition monitoring but these are likely to affect non-technical aspects. As an example, wanted monitoring system output alone might not reduce costs but it decreases man hours which reduces costs and probably it also increases the staff motivation. Of course these technical goals should support the main goal.

Spare (2001) has studied a business case for condition based maintenance from electric utility point of view. According to Spare (2001) the expected benefits from condition based maintenance are divided into two different categories which are monetary and soft benefits. Listed benefits are following:

- Reduce maintenance costs
- Reduce catastrophic failures and collateral damage
- Defer replacement (extend life)
- Increase equipment utilization

- Reliability / availability
- Safety and environmental concerns

Last two of the benefits are categorized as soft values and rest of the benefits are monetary values. The benefits can also be thought as goals for maintenance. List clearly shows that these goals are all related to condition monitoring. This view is also supported by Abu-Elanien & Salama (2007: 187-191) as they have studied transformer condition monitoring in their article. According to their article condition monitoring is the technique served for condition based maintenance.

According to ABB (2000: 596-599) the goal for condition monitoring is to identify fault before major failures so maintenance activities can be planned. Another goal for condition monitoring is to give possibility to skip unnecessary maintenance breaks. Same source divides condition monitoring to detection, diagnosis and prognosis of fault, action proposal and root cause analysis.

ABB Transformer handbook (2004: 123) defines major goals for on-line monitoring system. The goals are to prevent major failures, to achieve better utilization of load capacity, optimize maintenance and to extend the remaining lifetime. These goals are more CBM related, which is supported by condition monitoring.

All sources are well lined up and there are no major differences between sources. Now it can be clearly stated that goal for maintenance is to support availability performance and condition monitoring is the tool to provide information for condition based maintenance. To be more specific with condition monitoring goals it can be concluded that those should be early detection, diagnosis and prognosis of fault. Action proposals and root cause analysis are more advanced goals for condition monitoring. As it was defined in the introduction chapter this thesis will concentrate on early detection of faults.

3. CONDITION MONITORING GOALS BY STAKEHOLDERS

Condition monitoring goals from literature were briefly covered in the second chapter, but stakeholder goals are needed before it is feasible to research the subject. In the chapter two it was defined that condition monitoring is part of condition based maintenance (CBM). Conclusion was that CBM strategy defines the higher level goals which are then supported by condition monitoring. Goals can be defined by several different stakeholders and also the point of view varies by different stakeholders. As an example power plant end user is interested about maintenance strategies and condition monitoring system provider is more or less looking the subject from the monitoring point of view. Power plant owner is normally the stakeholder who defines the maintenance strategy as the financial aspects are also part of the process.

This chapter will introduce goals defined by several different stakeholders. Questionnaire was based on Delphi method which is explained later. The goal for the questionnaire was to find out present situation with condition monitoring and also to have common goals for the future regarding condition monitoring. Interviewed persons represented following stakeholders

- Power plant manufacturer
- Transformer manufacturer
- Distribution utility
- Transmission utility

The questions were the same for all the interviewed stakeholders. Questions could have been more specific for each stakeholder but this way it was possible to get different aspects by using same approach for each stakeholder. The questionnaire included following questions:

- How do you see the role of different maintenance strategies in general as a <stakeholder>?
- What about power transformer maintenance?

- How do you see the role of automated on-line condition monitoring related to maintenance as a <stakeholder>? What are the main pros and cons?
- Are your customers confident in automated condition monitoring? Does it provide additional value to your customers? Are they willing to pay for the added value?
- When do you think that 20 % of your customer will have automated condition monitoring?
- How do you see the reliability of automated condition monitoring? What are the main pitfalls with automated condition monitoring?
- How you will see the future of condition monitoring in general?
- What is still missing from the condition monitoring in general?
- What expectations you have for transformer condition monitoring? (e.g. output, monitoring system lifetime, service interval, price range?)

3.1. Introduction to Delphi method

The Delphi method is a systematic, interactive forecasting method where information comes from a panel of independent experts. The carefully selected experts answer questionnaires in two or more rounds. After each round, a facilitator provides an anonymous summary of the experts' forecasts from the previous round as well as the reasons they provided for their judgments. Experts are encouraged to revise their earlier answers in light of the replies of other members of their panel. It is believed that during this process the range of the answers will decrease and the group will converge towards the "correct" answer. Finally, the process is stopped after a pre-defined stop criterion (e.g. number of rounds, achievement of consensus or stability of results) and the mean or median scores of the final rounds determine the results. (Schniederjans, Hamaker & Schniederjans 2004: 170-172; Wikipedia 2009.) The same method was also known with terms Delfi and Delfoi (Kuusi 2009).

3.2. Result of the questionnaire

This questionnaire is a light version of Delphi method as there are only few experts to be interviewed. It means that more critical approach is needed when results are interpreted.

3.2.1. Present situation and background

Time Based Maintenance has been the basis for maintenance for a long time and it is still a big part of it. Around ten years ago Condition Based Maintenance was introduced and it is getting more popular all the time. Reliability Centered Maintenance is the next step from Condition Based Maintenance and it will gain popularity but it will take time. Asset management was also mentioned and it seems to draw more attention in electric utility world.

Condition monitoring services within power plants are not very popular at the moment. Within electric utilities there are few examples of companies who use some automated condition monitoring. The main reason for this would be that many stakeholders have gaps in knowledge regarding condition monitoring and Condition Based Maintenance. Partly it is a result from limited offering of condition monitoring systems. Primary device manufacturers have more information about monitoring but they are not keen to promote it as it gives the impression that their products are unreliable. This environment doesn't give very good base for condition monitoring knowledge to grow. There is also the weight from history: "Things were done this way for past 20 years so we continue in the same way". It's a long journey to change attitude for different stakeholders.

Power transformers are kept as devices which will not brake down during the lifecycle and are kept as very static products. This makes it very difficult to market transformer condition monitoring for the customers when you combine it to the fact that no one is marketing monitoring system for them except individual monitoring component manufacturers. Condition monitoring is usually ordered together with transformer if customer demands it and buying decision is not triggered by active marketing. This probably means that stakeholders who have expectations for cost and risk optimization

will order monitoring system. This is happening in modern electric utilities as their interest towards condition monitoring and preventive actions against failures in general has increased. Main reasons for this are smaller tolerances for electric disturbance and outage compensations for customers. In some special cases also risk management is a good motivation. As an example underground substations need risk management. Electric utilities are having pilot projects to benchmark current situation of condition monitoring but the findings have not been satisfactory at all. In other words they are waiting for complete turnkey solution which is good-enough and affordable to be implemented with the whole transformer fleet.

Automated condition monitoring is one of the many tools used for decision making in maintenance. As an example, analyse of an expert is one of the other tool for decision making. It is also important that maintenance personnel visit the site on regular basis to visually check that everything is ok. Of course it is possible to make visits with longer interval if condition monitoring is used successfully. The general opinion based on interviews seems to be that optimal solution for maintenance decision making would be combination of different tools like personnel visits, automated condition monitoring, expert analysis and regular service intervals depending on age of devices.

At the moment Dissolved Gas Analysis (DGA) is kept as a best option for condition monitoring and especially if it's made automatically. The advantage of automatic samples is consistent conditions. Failures can develop even within 50 hours so it is essential to get DGA samples frequently. The major problem with existing DGA devices is reliability. At the moment devices sends false alarms, even the most expensive ones. Devices also tend to break already after five years of service, which is unacceptable.

At the moment all condition monitoring devices are separate products so every monitoring system needs to be tailored for its purpose. Measurement devices use different communication protocols and also the devices are designed with totally different philosophies, which create problems when building monitoring system. Price is also kept as problem. For example DGA devices cost between 15 000 and 50 000

euros. Complete monitoring system for one transformer can cost over 100 000 euros and that is too much according to the stakeholders.

3.2.2. Challenges and possibilities of condition monitoring

Biggest challenges in the near future are to provide accurate and understandable information for the end users. The main pitfall is definitely unreliable information. If there is even a one inaccurate message for the customer about an evolving fault in the system, the condition monitoring system loses its creditability. It is much better to detect one fault out of 100 and to do it with 100 % reliability rather than 50 faults with 50 % probability. It is commonly agreed that automated condition monitoring should work as decision making tool for maintenance activities. On the other hand there are variations about the user of the output from condition monitoring system. Options are electric utility personnel (control room personnel and experts) and 3rd party service provider. It should be only used as a tool for the experts to make analyses.

Second challenge, which is present already today, is the experience and expertise of monitoring personnel. There are people working with control and monitoring systems who doesn't have hands on experience about monitored devices. Current situation is that condition monitoring systems don't support decision making as the information is not understandable for most of users. This leads to a situation that control room personnel are not capable to decide maintenance actions, so experts are needed for decision making. This also gives challenges when designing the system.

Condition monitoring and maintenance doesn't have any standard, which is a major problem. Also a question was raised that why big energy related companies won't start a common project to develop the framework for maintenance and asset management. There are also quite many expectations for IEC 61850 although there are still connectivity problems between devices. Status of device level communication (e.g. IEC 61850) is pretty good but the major problem is the umbrella on top of it. The questions are:

- How to analyze data?

- Where to analyze data?
- Who should be able to connect to the system?
- What system should cover?
- How information is transferred from sites to control rooms?
- Etc...

Condition monitoring has many advantages like oil samples are taken under consistent conditions, history is stored and in some cases there is no need to take manual samples. On the other hand the samples might not be as accurate as with manual samples and the price for monitoring system may rise quite high.

3.2.3. Trends for maintenance and condition monitoring

Maintenance methods are going towards asset management although it will take several years before it is widely used. It was also mentioned that there is a need for one single key figure which would indicate the status of whole substation or power plant. This figure would be calculated from several parameters like plant criticality and health of primary components. Also power quality was mentioned as a possible trend. Power quality requirements have been increased and it costs more money to produce electricity with good-enough quality. The question was raised if it is possible to sell electricity with different quality levels. These are major changes and actually these would refresh whole electric utility industry. It means that way of thinking of personnel must be changed as all possible data is important for the overall picture and many tasks must be thought from new angle. In the beginning the costs will increase as more training is needed and devices are more expensive. At the moment ways of working are quite stable and field proven with many stakeholders so changing those is very challenging. This could lead to a situation where new methods are actually the correct way of working but implementation is too time consuming leading to very high costs and the original way of working is taken back in to use.

One trend is that condition monitoring is expected to be integrated to primary devices. Main message is that the amount of sensors must be minimized and the overall investment shouldn't be low as possible. This can be transformed also to a statement

that all data gathered from condition monitoring system should be utilized with better efficiency. This means that the system should contain less sensors and more software based analyzes. Integration can also affect the delivery process because sensors must be installed while transformer is manufactured. It would need much better knowledge of automation technologies from transformer manufacturer. This trend may also create challenges from system architecture perspective and in the beginning this will most likely cause problems with deliveries. These problems should be temporary but still there is a lot of work to do when changing the perception of stakeholders. This will most likely lead to a same situation as earlier, meaning that implementation takes too much time which leads to very high overall costs and again the original way of working is taken back in to use.

Based on interviews, condition monitoring devices should be developed towards protection devices from design point of view. Meaning that devices are designed to work around twenty years only with some calibration and testing at the same time when other parts of secondary system are tested.

It is important that the investment cost is decent, despite of possible savings and transformer size. Based on one interview price is acceptable if it is around half of the savings what can be achieved with system. Another approach for the costs is that condition monitoring implementation should cost maximum 5 % of overall transformer investment. The expectations are that within 10 years there will be a transformer condition monitoring system installed for all new 100 MVA power transformers. With current product offering these price limits rules out a lot of monitoring solutions which means that reliable monitoring system is very challenging to achieve.

Common message of the interviews is that maintenance related activities and automated condition monitoring will grow in the near future. It's also clear that maintenance activities, maintenance management and system monitoring will be fully outsourced by most companies as maintenance is getting bigger and more important. For most companies this is the easiest solution to handle maintenance activities but on the other hand the knowledge is lost from the company and also costs might rise with outsourcing.

There are two main reasons why condition monitoring solutions will be developed in the near future. These are customer expectations and car industry as a driver. Customer expectations will grow during the time when monitoring solutions gets wider acceptance. Car industry is already more advanced in monitoring compared to electric utility business which might give ideas and technological solutions for condition monitoring in other businesses.

3.3. Conclusions from the questionnaire

In general Delphi method seems very useful and interviews were effective. On the other hand it was difficult to receive feedback for the summaries. This method has also challenges when selecting the correct experts and to find enough experts who are interested about specified subject. After first Delphi experience it is probably easier to create a new Delphi questionnaire.

It seems that condition monitoring and condition based maintenance is getting more focus all the time but there is also doubts with maintenance and condition monitoring. There are several reasons for challenges like staff attitude, lack of knowledge, implementation costs and quality of equipment. Wang, Vandermaar & Srivastava (2002: 21) mention in their article that the main reasons for slow implementation of transformer condition monitoring are costs, data interpretation, reliability and compatibility. Most of these items were actually mentioned in the results of the questionnaire. The gap between these two sources is seven years which is a clear indication of very slow responsiveness in the industry. Based on this survey there seems to be expectations and needs for condition monitoring which is a positive sign. Comparison to car industry proves that some stakeholders have already studied condition monitoring and there is motivation to develop it.

It can be concluded that atmosphere is getting more suitable for transformer condition monitoring but there is still plenty of challenges with high costs and unreliable results.

4. POWER TRANSFORMER CONDITION MONITORING

This chapter will cover structure and aging of power transformer. Also possible failure causes and probability of faults in power transformers are covered. Last part of the chapter will handle on-line condition monitoring methods and devices.

4.1. Structure of a power transformer

As stated in introduction chapter the thesis covers only the most common power transformers in power plants. These are usually between 50 MVA and 120 MVA.

Generator step up (GSU) type power transformers are used on power plant applications. These transformers take voltage from the generator voltage level up to the transmission voltage level, which normally is around 110 kV. Figure 3 shows a picture of generator step-up transformer. According to ABB Transformer Handbook (2004: 18-19) step up transformers are usually Ynd-connected. It seems that there are many reasons why the low voltage winding should be connected in delta instead of star:

- The delta-connected winding keeps the zero sequence impedance of the transformer reasonably low.
- For large transformers the line current on the low voltage side is very high. In a delta-connected winding the current through the winding is equal to the line current divided by $\sqrt{3}$, which makes the winding work in the factory easier with a correspondingly smaller bundle of winding conductors. (ABB Transformer Handbook: 18–19.)

The high voltage neutral is in most cases solidly earthed and the insulation in the high voltage winding is graded which means that the insulation level in the neutral is lower than in the phase end of the winding. (ABB Transformer Handbook: 18-19.)

According to Virtanen (2009a) this size of transformers normally use ONAF (oil natural and air forced) cooling. It means that fans are to used blow air on to the cooling surfaces

of the radiators and oil is kept in circulation by the normal convection force in the closed-loop cooling system (Kulkarni & Khaparde 2004: 371-372).



Figure 3. Picture of generator step up transformer (ABB 2010).

4.2. Transformer aging

Transformer aging is one reason why condition monitoring is researched. Aging will cause outages, which creates losses for power plant owner. According to ABB (2004:117) transformer aging is related cellulose materials as those undergo chemical degradation in service. Cellulose materials are used as dielectric around transformer windings. This chemical degradation basically means old paper breaking up into small flakes. The dielectric insulation properties are only slightly affected in this state. More relevant risk is mechanical rupture and metal-to-metal contact as a result of mechanical shocks and vibrations (ABB 2004: 117.)

According to Koltunowicz, Bajracharya & Djairam (2009:1) aging is influenced by several factors like temperature, humidity, loading and power quality. They see power

quality as an increasing problem in form of very fast transients (VFT) and lightning surges. Figure 4 shows effected transformer components for each aging factor.

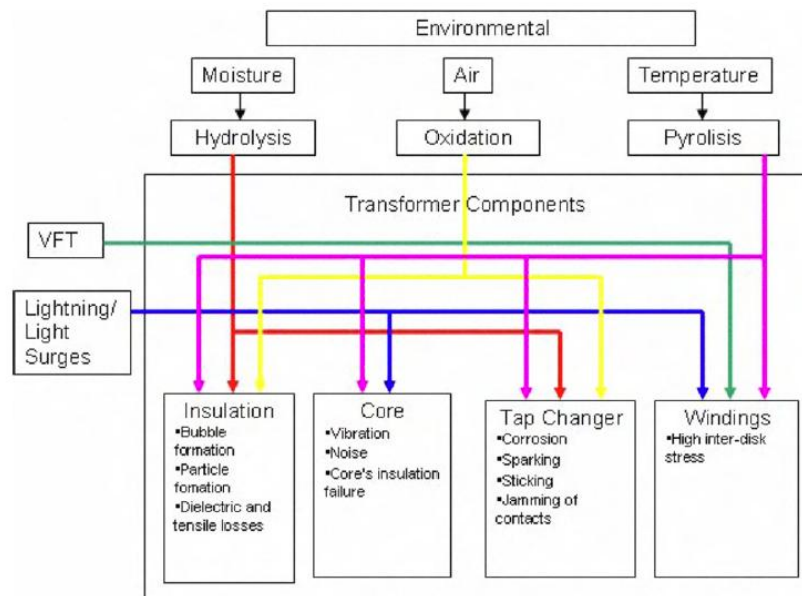


Figure 4. Aging factors and their effect on the main transformer components (Koltunowicz etc. 2009:1).

According to Koltunowicz etc. (2009) humidity is dangerous for the transformer as it deposit itself on the tank and slowly turn into rust and that can cause causing leakages. It can also penetrate into the insulation layer adding moisture to the oil paper insulation. The insulation has some moisture in the beginning. Elevated temperatures will cause this moisture to leave the paper and cold temperatures vice versa. With frequent fluctuations, the paper's ability to reabsorb the moisture decreases. Over time the permanent moisture level will increase leading to breakdown.

ABB (2004: 117) states that chemical deterioration process is doubled for each 6-7 °C temperature rise and this rate is considerably increased by the presence of water molecules and free oxygen dissolved in the oil. It is also clear that transformers continuous load capacity varies at different ambient air temperatures. IEC have created a loading guide for oil-immersed transformers and the guide has identification number 60076-7.

Koltunowicz etc. (2009) claims that fast switching functions used by power electronics cause serious harm to the insulation layers of capacitive objects such as the transformer's winding. For example AC/DC and DC/AC converters are common applications for power electronics and these converters are often used in wind farms and HVDC substations. Koltunowicz etc. (2009) base their claim on a test where two square waveforms of amplitude 4 kV and 5kV were applied to two wires with a layer of insulation. The result is that after 5 kHz the characteristic of time to failure changes as seen in Figure 5.

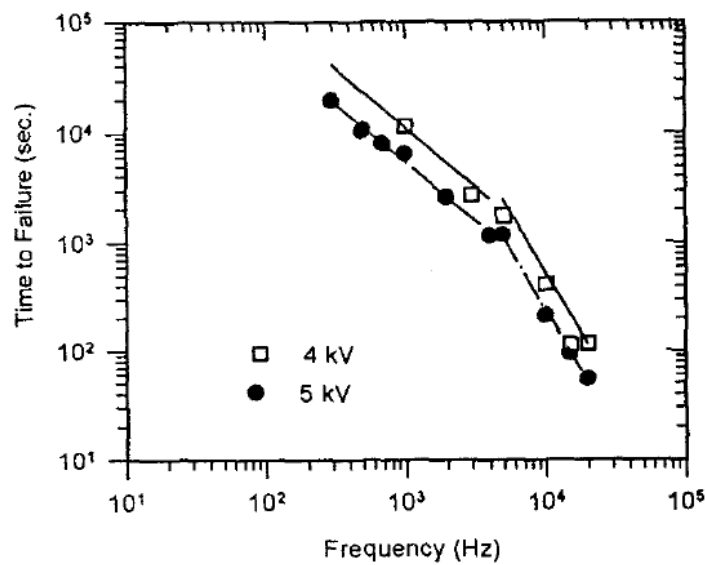


Figure 5. Time to failure at different frequencies between two magnet wires (Koltunowicz etc. 2009).

4.3. Possible faults and statistics

Several different parties have studied transformer failure statistics. Some of these are introduced here and the goal for this chapter is to define the major failure areas with power transformers.

According to ABB Transformer Handbook (2004: 118) failure rate of large power transformers due to short circuit currents was very low, 3 failures per 25000 transformer

service years. Of course this excludes all other failures causes, which likely have a major effect to the failure rate. Sokolov (2006: 1) says that many-sided observation on transformer reliability was presented in CIGRE survey at 1983. It summarized over 1,000 failures of power transformers rated 72 kV and above for the period 1968-1978. It was revealed that the annual failure rate for all power transformers was 2 %, and for extra high-voltage transformers it may be 5 %.

4.3.1. Analysis by William H. Bartley

William H. Bartley (2003) has done an analysis of transformer failures. The scope for this analysis was damaged transformers rated at 25MVA and above during the period 1997 through 2001. Requested information included year of loss, size in MVA, age at failure, application (utilities, industrials etc.), cause of failure, property damage portion and business interruption portion. For some cases Bartley were not able to identify the age of the transformers and in some cases the size of the transformer. All amounts of losses were converted to U.S. dollars, using the following exchange rates: 0.9278 euros; 8.542 Swedish kronas; and 6.0858 French francs. (Bartley 2003: 1.)

The total amount of property damage was 163 million US dollars, i.e. an average amount of 1,73 million dollars per damage. The total value of the losses resulting from business interruption was 123 million dollars, i.e. an average of 1,31 million dollars per loss. One business interruption loss resulting from the destruction of a power plant's transformer totaled 87 million dollars. This single loss increases the average value of a loss resulting from business interruption almost fourfold. (Valta 2007)

Numbers from the transformer failure analysis are covering all transformer failures but this research is focusing on generator step up transformers. Bartley's research had also an analysis by application of transformers. See Table 1 for losses by application. It can be clearly seen from the figures that generator step-up transformer failure cause major amount of expenses. The amount of failures is almost even between generator step up and utility substation transformers but total losses are over ten times bigger with generator step up transformers compared to Utility Substations.

Table 1. Losses by application (Bartley 2003).

Year	Generator Step Up		Industrial		Utility Substations		unknown		Annual Totals	
1997	\$ 29,201,329	3	\$ 2,239,393	4	\$ 5,243,075	11	\$ 4,095,710	1	\$ 40,779,507	19
1998	\$ 15,800,148	8	\$ 3,995,229	6	\$ 5,136,858	11			\$ 24,932,235	25
1999	\$ 3,031,433	4	\$ 24,922,958	4	\$ 6,116,535	6	\$ 3,320,665	1	\$ 37,391,591	15
2000	\$ 123,417,788	10	\$ 24,724,182	4	\$ 2,039,810	6			\$ 150,181,779	20
2001	\$ 32,082,501	11			\$ 1,261,199	4			\$ 33,343,700	15
Totals	\$ 203,533,199	36	\$ 55,881,762	18	\$ 19,797,476	38	\$ 7,416,375	2	\$ 286,628,811	94

Bartley's analysis divided failure causes into several different categories and the categories were:

- Insulation Failures - This category excludes those failures where there was evidence of a lightning or a line surge. According to Bartley's analysis there are four factors that are responsible for insulation deterioration: pyrolosis (heat), oxidation, acidity, and moisture. Moisture is reported separately. The average age of the transformers that failed due to insulation was 18 years.
- Design /Manufacturing Errors - This category includes conditions such as: loose or unsupported leads, loose blocking, poor brazing, inadequate core insulation, inferior short circuit strength and foreign objects left in the tank.
- Oil Contamination – This category includes those cases where oil contamination can be established as the cause of the failure.
- Overloading - Includes those cases where actual overloading could be established as the cause of the failure. It includes only those transformers that experienced a sustained load that exceeded the nameplate capacity.
- Fire /Explosion - This category includes cases where a fire or explosion outside the transformer can be established as the cause of the failure. This does not include internal failures that resulted in a fire or explosion.
- Line Surge - This category includes switching surges, voltage spikes, line faults/flashovers and other abnormalities.

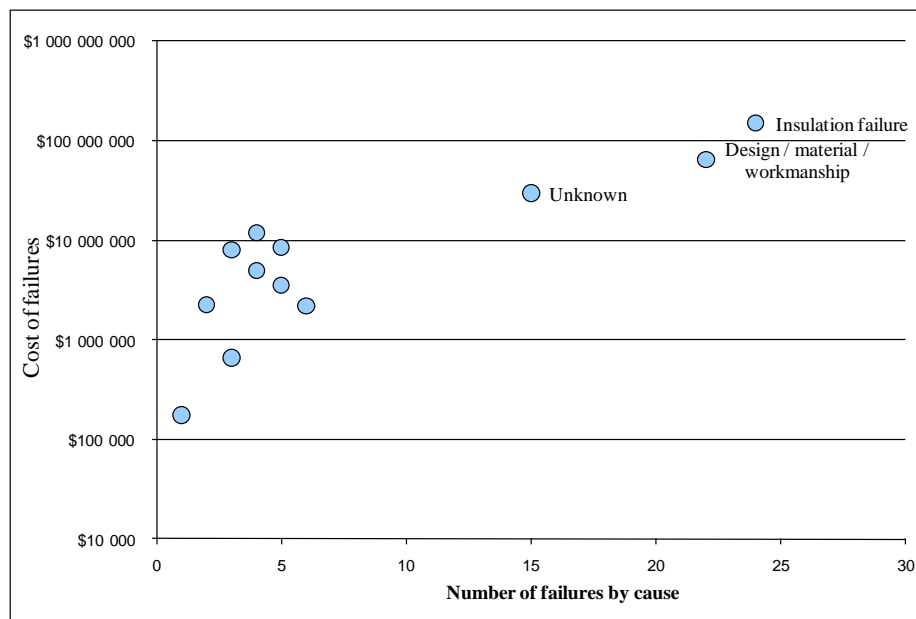
- Maintenance/Operation - This category includes disconnected or improperly set controls, loss of coolant, accumulation of dirt & oil and corrosion. Inadequate maintenance has to take the blame for not discovering incipient troubles when there was enough time to fix it.
- Flood – The flood category includes failures caused by inundation of the transformer due to man-made or natural caused floods. It also includes mudslides.
- Loose Connections - This category includes workmanship and maintenance in making electrical connections. According to Bartley’s analysis one problem is the improper mating of dissimilar metals, although this has decreased somewhat in recent years. Another problem is improper torquing of bolted connections. Bartley’s analysis states that loose connections could be included in the maintenance category but it was reported separately.
- Lightning - Unless there is confirmation of a lightning strike, a surge type failure is categorized as “Line Surge”.
- Moisture - The moisture category includes failures caused by leaky pipes, leaking roofs, water entering the tanks through leaking bushings or fittings, and confirmed presence of moisture in the insulating oil.

Table 2 shows distribution between failure types. The original table is appended with proportion of failures column. This table is covering whole analysis data and it is not limited only to generator step up transformer failures. The table shows that the three biggest failure types are causing over 60 % of all failures. It can be also noted that 29 % of all failures cannot be predicted with condition monitoring system if we include external failures causes Unknown, Fire / Explosion, Line Surge, Flood and Lightning. Unknown can be either external or internal failure cause, so this adds uncertainty aspects to the 29 % and most likely the real value is significantly smaller.

Table 2. Cause of failures (adapted from Bartley 2003).

Cause of Failure	Number	Total Paid	Proportion of failures
Insulation failure	24	\$ 149 967 277	26 %
Design / Material / Workman ship	22	\$ 64 696 051	23 %
Unknown	15	\$ 29 776 245	16 %
Oil Contamination	4	\$ 11 836 367	4 %
Overloading	5	\$ 8 568 768	5 %
Fire / Explosion	3	\$ 8 045 771	3 %
Line Surge	4	\$ 4 959 691	4 %
Improper Maintenance / Operation	5	\$ 3 518 783	5 %
Flood	2	\$ 2 240 198	2 %
Loose Connection	6	\$ 2 186 725	6 %
Lightning	3	\$ 657 935	3 %
Moisture	1	\$ 175 000	1 %
Total	94	\$ 286 628 811	100 %

Based on the figures in Table 2 a chart showing relation between amount of failures and cost can be created. Figure 6 shows the total risk between different fault types. Three highest are clearly the most important according to this study. These three are Insulation failure, Design/Material/Workmanship and Unknown.

**Figure 6.** Frequency versus Severity of Transformer Failures (Bartley 2003).

Bartley's analysis gives good overview about different types of failures from short period of time. One problem is that these results are not reflected to the installed base of power transformers so it is impossible to get failure rate from this data.

4.3.2. Analysis by Victor Sokolov

Victor Sokolov (2006) has analyzed different transformer failure analysis and suggests some typical failure modes in his white paper. Table 3 shows the data for different surveys. Please note that the columns are not comparable. According to Sokolov the data shows that failures have been mostly related to damage of windings, bushings and on load tap changer (OLTC). Data sources for the surveys are very different as well as the timeframe, also application areas differ. This makes it more difficult to form a clear indication of overall situation but it gives indication of possible faults and which one of those are more critical than others.

Table 3. Failed components and failure modes (Sokolov: 2006).

Faulty component	CIGRE Survey 1983,%	IEEE 1986,%	EPRI GSU US %	Australia- New Zealand 1985-95 %	India Power Grid	China 220kV numbers
Windings/insulation	29	41		30	73,3*	21
Dielectric issues			21			
Mechanical			11			
Magnetic circuit	11	10				4
Terminals	29	9	5			
OLTC	13			25		15
Bushing	5	13	30	19	13,3	45
Tank and dielectric fluid	13	3				16
Cooling & Others		17	12		13,3	22
Total failure observed	>1000	164	45	498	15	176

* Including two cases due to water entry through bushing

Sokolov had also another analysis between different statistics, see Table 4. Comparison includes transformer failures over 100 MVA. ZTZ-service cases are divided into generator step-up and transmission transformer failures. These are also compared to data reported by Doble clients. Sokolovs conclusion was that failure profile consists of wear-in, which is followed by random failure period. Average failure rate remains on the level of 1 %. Source does not mention if average failure rate is annual, but it is assumed here. He also brings up the fact that almost 10 % of failures occurred with new transformers according to these figures. He also noted that Cigre discussion has admitted that the interest on the reliability of new transformers is increasing and unreliability might be a result of structural changes in the industry: globalization of manufacturers and restructuring of utilities.

Sokolov also claimed that for the last years a novel failure have occurred, which has been associated with corrosive oil and winding insulation failure due to conductive deposit of copper sulphide on paper insulation. Over 40 transformers and shunt reactors has a failure and those occurred constantly in hot area (i.e. Colombia, Brasilia, India, Rwanda, Thailand, Italy and Southern USA). Typical failure mode was short-circuit between turns in upper part of a winding.

Table 4. Major failures of power transformers rated 100 MVA and above (Sokolov 2006: 4).

Failure mode	Component	Doble clients 1996- 1998 %	ZTZ-Service 2 2000-2005, %	
			GSU	Transmission
Dielectric	Winding minor insulation	23	37,8	14,3
	Major insulation	13,4	11,2	17,3
Thermal	Conductor insulation	5,8	13,3	4,8
Mechanical	Winding distortion	12,5	4,4	9,5
Magnetic circuit	Core/magnetic shields*	5,8	4,4	4,8
Current carrying	Leads, connection	3,8	13,3	3,2
	Bushing	9,6	13,3	38
	OLTC**	15,4	4,4	7,9
Accessories	DETC	3,8	2,1	0
Others		6,9	0	0
Total number of failures		52	45	63
Average age		22,4	21	20,5
Over 25 years, %		43	44,1	32
Less than 5 years, %		7,5	2,94	9,4

* Only force outages considered

** Only major failures

Sokolov claims that transformer application has a great effect to possible failure mode. Most likely that is correct as usage differs with different types of transformers (e.g. generator step-up transformer compared to transmission transformer). He divided failure modes into three application categories, which were transmission, generator and auxiliary power plant transformers. For generator transformers the failure modes were:

- Windings (HV) insulation
- Trend to increasing thermal failures
- Leads and connections overheating

By looking the results also the bushing failures should be added to the list, as the failure rate is equal to thermal failures as well as to lead connections failures. Sokolov defines failure modes in the following way:

- Major insulation – This category includes failure modes of oil gap breakdown, surface contamination and degradation of impulse strength as well as critical over voltage.
- Minor winding insulation (coil-to-coil, turn-to-turn) – Failures in this category occurred predominantly on HV side windings (about 80 %) and fairly stressed regulating windings. Failure modes were free water enter, oil contamination, oil degradation, wearing out of tap coils of HV side winding, underestimated impulse over voltage and poor performance. Three failure mechanisms have been typically involved: Breakdown of oil gap, Surface discharge and creeping discharge.
- Thermal-mode failures – This category includes following failure modes: overheating of tap leads located between regulating coils of HV winding connected to no-load tap changer, overheating of the coils of winding blocked with angle collars preventing oil flow and proper cooling and underestimation of winding temperature.
- Damage of wires and connections – Three failure modes were included in this category: overheating the insulation of winding exit leads, overheating soldered connections and overheating bolted connection to bushings.
- Mechanical mode failures – This category includes winding movements.

4.3.3. Other analyzes

Jongen, Morhuis, Smit, Janssen & Gulski (2007) have approached power transformer failures from a different angle. First of all the base data is different and also the categorization is different. Their analysis is performed for a population of power transformers with a power rating starting at 14 MVA up to 175 MVA. The range of service life is from one up to 55 years. The average age of the total population is 29 years and total population is almost 500 transformers in service.

Categorization of the failures is the same what has been used in Cigré's report from 1983. These are done by failed components rather than failure cause:

- Tap changer - This includes the off-load as well the on-load tap changer
- Leakage - Problems concerning the tank and the dielectric fluid
- Bushings
- Windings - Short circuit of the windings of a transformer
- Core - Problems concerning the magnetic circuit
- Other - e.g. temperature problems

The occurrence of failures is graphically shown in Figure 7 and Figure 8. Figure 7 shows data from Cigré report from 1983 and Figure 8 shows failure occurrences from analyzed transformer population. The failure statistics of Cigré consists of approximately 800 failures and the number of reported failures in analyzed data is only about 50.

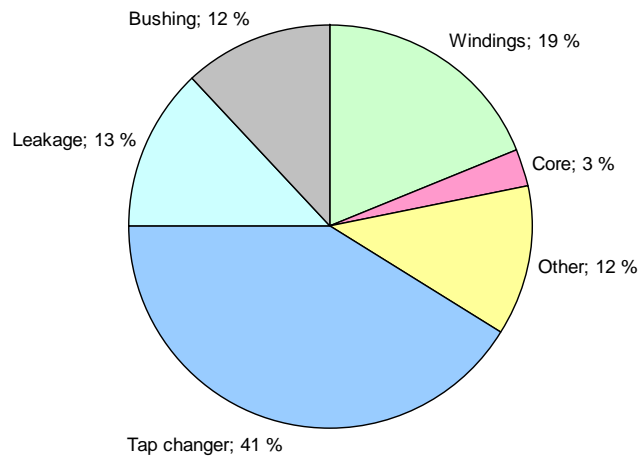


Figure 7. Cigré data (Jongen etc. 2007).

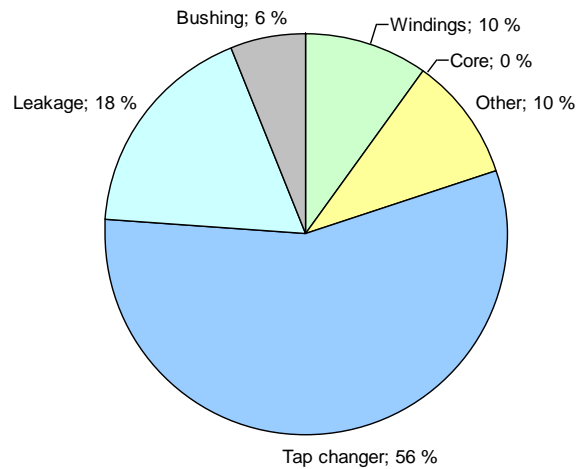


Figure 8. Local failure data (Jongen etc. 2007).

This analyze will give us some indication about component failures. If we leave tap changer out from the failed components, we can see that Leakage, Windings and Bushings are causing majority of the failures.

4.3.4. Conclusion

Average age for transformers based on statistics is around twenty years, but varies between countries as in Finland the average age is over thirty years based on the questionnaire made in this thesis. There were also opinions that quality of new transformers is decreasing and this would increase transformer failures in the near future.

Different sources have different approaches to failure statistics but it is still quite obvious which are the most common and most important failures that should be covered with condition monitoring. Tap changer failures are left out from this conclusion as power plants normally don't have tap changer or the usage is very minimal. External failure causes like lightning, flood and fire are also excluded from the list. Possible internal failure causes are listed below and first one is rated as most important.

- Insulation deterioration - By the results from different analysis it is clear that insulation deterioration is causing most of transformer failures. This includes both main tank and bushings. Both winding insulation and bushing failures were on top of the list in majority of the analysis.
- Maintenance & operation – Second largest reason for failures is for poor maintenance and operation. Inadequate or improper maintenance and operation was a major cause of transformer failures if overloading, loose connections and moisture/leakage are included maintenance & operation category.
- Design & manufacturing - Third largest reason for failures is design and manufacturing failures. This was only coming up in the Bartley's analysis but it had a major influence so this needs to be considered too.
- Mechanical – Fourth is mechanical failures. This basically includes winding deformations. This doesn't seem to be a major failure cause for generator step-up transformers but still needs to be counted.
- Core - Core failures are uncommon based on these statistics.

The next question is how these can be detected with condition monitoring. This question will be handled in the next chapter.

4.4. Condition monitoring methods for power transformer

Earlier chapter introduced the known faults, which might be faced during a life cycle of a power transformer. According to Rudd, Catterson & McArthur (2008: 1716) several methods are needed to find out the fault as early as possible. This claim is in line with the results from earlier chapter as several different components or aspects can cause failures. This chapter will introduce different condition monitoring methods and make a link to which failures that specific method can be used.

Abu-Elanien and Salama (2007) have studied different methods to handle transformer condition monitoring. Abu-Elanien & Salama have divided methods into five main categories. The categories are thermal analysis, vibration analysis, dissolved gas

analysis, partial discharge analysis and frequency response analysis. According to the article the categories are based on several researches during past years. Methods listed by Abu-Elanien etc. (2007) are only covering the main tank but not the accessories. As mentioned earlier, the accessories are essential part of the transformer so we need to have monitoring method also for cooling and bushings. Abu-Elanien etc. have also included frequency response analysis which will be left out from this study as it is mainly used as an off-line method (Abu-Elanien 2007: 190).

Lord & Hodge (2007) have a slightly different approach to different condition monitoring as they are studying component monitoring rather than different methods. Lord etc. (2007) includes accessories in the components. Their condition monitoring subjects for the main tank are:

- Moisture in oil
- Oil signatures from winding connection issues
- Winding hot spot temperature
- Winding insulation degradation
- Core and winding geometry
- Main tank electrical and acoustic partial discharge (PD)

These subjects are mostly related to Abu-Elanien etc. (2007) categorization. Moisture in oil and core and winding geometry are additions to the earlier categorization. For bushing monitoring Lord etc. (2007) are suggesting tan delta monitoring as a good option. For cooling monitoring they are suggesting to monitor fans contactor operation at minimum level. Advanced option monitoring would include current measurement. All covered monitoring methods are suitable for automated transformer condition monitoring.

Any of these articles are not including loading as a condition monitoring method. One major failure cause was improper operation and overloading is included in this part so it would make sense to use loading information in condition monitoring.

Following sections introduce most essential monitoring methods for this research and the methods are thermal analysis, vibration analysis, partial discharge analysis, dissolved gas analysis, moisture analysis and bushing monitoring.

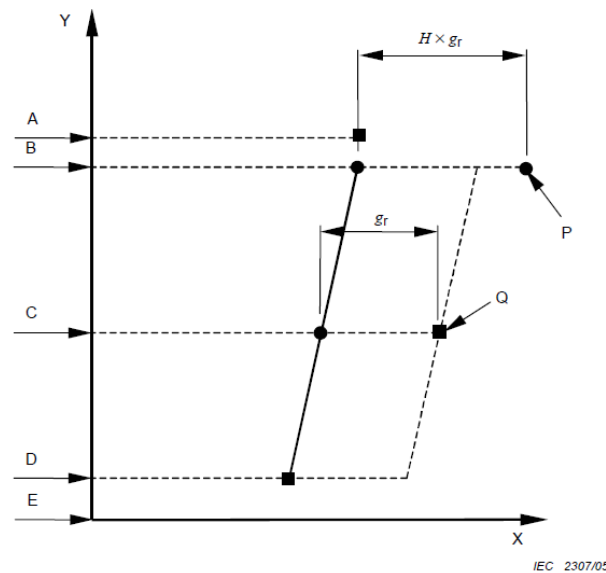
4.4.1. Thermal analysis

According to Abu-Elanien etc. (2007) thermal analysis of the transformers can provide useful information about its condition and it is possible indicate any incipient fault inside it. Many of the incipient faults cause a change in the thermal behavior of the transformer. It is commonly accepted that transformer life can be affected very much for a continuous maximum hotspot temperature of 98°C on the paper insulation. Abu-Elanien etc. (2007) continues that from that point onwards it is assumed that the rate of ageing doubles for every increase of 6°C as explained earlier in chapter 4.2. Also, the transformer oil is subjected to degradation due to direct thermal effects, and increased oil temperatures are likely to accelerate other ageing processes (Abu-Elanien etc. 2007).

Abu-Elanien etc. (2007) divides temperature analysis into two categories. The first category is related to artificial intelligence techniques to predict the transformer temperatures. The second category is about developing a thermal model to predict the thermal behavior of the transformer. (Abu-Elanien etc. 2007.)

Abu-Elanien claims that artificial neural network is a very good predictor for the transformer hot spot and top oil temperatures. Assumed main inputs for the system to predict mentioned temperatures would be three phase currents measured from the transformer and surrounding weather conditions. More inputs to the software can be used to enhance the accuracy of the prediction of the top oil and hot spot temperatures like previous predictions. (Abu-Elanien etc. 2007.) IEC defines hot-spot modeling in loading guide for oil-immersed power transformers (IEC 60076-7) and it is presented in Figure 9. It is a simplified model and it doesn't cover surrounded weather conditions or three phase currents. IEC (IEC 60076-7: 21) also notes that the hot-spot temperature should be referred to the adjacent oil temperature. Source assumes this to be the top-oil temperature inside the winding. According to same source measurements have shown that the top-oil temperature inside a winding might be up to 15 K higher than the mixed

top-oil temperature inside the tank. For most transformers in service, the top-oil temperature inside a winding is not precisely known. On the other hand, the top-oil temperature at the top of the tank is usually well known either by measurement or by calculation. IEC (IEC 60076-7: 21.)



Key

- A Top-oil temperature derived as the average of the tank outlet oil temperature and the tank oil pocket temperature
- B Mixed oil temperature in the tank at the top of the winding (often assumed to be the same temperature as A)
- C Temperature of the average oil in the tank
- D Oil temperature at the bottom of the winding
- E Bottom of the tank
- g_r Average winding to average oil (in tank) temperature gradient at rated current
- H Hot-spot factor
- P Hot-spot temperature
- Q Average winding temperature determined by resistance measurement
- X-axis Temperature
- Y-axis Relative positions
- measured point; ● calculated point

Figure 9. Thermal diagram for hot-spot modelling (IEC 60076-7: 22).

Second category is related to developing a thermal model for the evaluation of the transformer thermal behavior. Abu-Elanien etc. (2007) claims that transformer thermal model was discussed in many publications with different accuracies and different building techniques. The source continues that there was a relation between the thermal and the electrical circuits. Source claims that this thermal model can be used to make

on-site condition monitoring of the transformer and provide engineers with real time data monitoring. Model would determine the water in oil, water in paper and temperature calculation of the power transformer. (Abu-Elanien etc. 2007.) Paper doesn't present any concrete examples or methods, so this second category should be interpreted more carefully.

Temperature monitoring is a very cost-effective way of having transformer monitoring. This method is also already used. Biggest advantage for temperature monitoring is that it is very cheap and robust method. Main problem with the method is the sensitivity. Basically it means that temperature measurement is not sensitive for quickly evolving faults. For aging modeling, it is kept as a good method and also necessary. As mentioned Abu-Elanien claims that temperature monitoring could be used for on-line condition monitoring together with artificial intelligence. Using artificial intelligence needs more research but could be one option for the future.

4.4.2. Vibration analysis

According to Abu-Elanien etc. (2007: 189) the usage of the vibration signals in evaluating the transformer health is a relatively new technique and its research is under development compared to the other methods of the transformer condition monitoring. The health of the core, windings and on load tap changer can be assessed using vibration signature of transformer tank (Abu-Elanien etc. 2007). Garcia, Burgos & Alonso (2006a, 2006b) confirm this in their articles, which introduce a method to detect winding deformations. These articles doesn't cover core or on load tap changer but it is still clear that vibration analysis is one possible method for power transformer condition monitoring.

According to Abu-Elanien etc. (2007: 189) the tank vibration consists of two different types and those are core and winding vibrations. These generated vibrations travels through the transformer oil until reaching the transformer walls. The vibration of the transformer can be measured via accelerometers from transformer walls. The vibration signal is a series of decaying bursts and each of the bursts is the result of a combination of a finite number of decaying sinusoidal waveforms. (Abu-Elanien etc. 2007: 189.)

Vibration analysis is definitely an on-line monitoring method, which can be handled automatically. The method has been tested with pilot projects but it still needs more research before it's widely accepted. It is an interesting method but as explained in failure statistics the problems caused by windings and core are minimal. Garcia etc. (2006a, 2006b) presents a more detailed description about their method and also some results from a test environment.

4.4.3. Partial discharge analysis

According to Abu-Elanien etc. (2007: 189) partial discharges occur in a transformer when the electric field strength exceeds the dielectric breakdown strength of a certain localized area. The insulation partially connects the conductors due to an electrical discharge or discharges. If consistent partial discharge activity is present for long periods of time, then the dielectric properties of the insulation may be reduced. This situation may result as a failure if the partial discharge activity remains. Researches into partial discharge phenomena in liquid dielectrics (such as oil) have been less common and are not as well understood as solid dielectrics. (Abu-Elanien etc. 2007: 189.) Source also mentions that large number of insulation problems starts with partial discharge activity and continues that partial discharge is considered as raw data that is used to perform the transformer condition monitoring.

Abu-Elanien etc. (2007: 189) mentions that on-line partial discharge measurement is usually affected by electromagnetic interference (EMI), which creates challenges when extracting the partial discharge signals from the measurement data. Source continues that this is because partial discharge signal magnitude is usually very low and the value of the partial discharge measurement signal from sensor is comparable with electromagnetic interference and cannot be distinguished by simple visual inspection. Abu-Elanien etc. (2007:189) says that it is required to apply some noise reduction techniques to achieve pure partial discharge signals. According to source the most common methods for de-noising are the Wavelet Transform, the gating method and the directional sensing.

According to Abu-Elanien etc. (2007: 189) the classification of a discharge depends on many factors but important features are the pulse amplitude, time of occurrence (point on wave) on the mains cycle, the number of discharges per second and the interval between discharges. Abu-Elanien etc. (2007: 189) continues that the partial discharge itself without interpretation is meaningless. It means that the data of partial discharge activity should be used to evaluate the condition of the transformer, to diagnose faults and to locate the origins of these faults. The partial discharge data is usually very large and because of that monitoring systems are often integrated with an artificial intelligence agent to sense the problem, identify its type and determine its location. (Abu-Elanien etc. 2007: 189.)

4.4.4. Dissolved gas analysis

It was mentioned earlier that transformer insulation is made from cellulose paper or pressboard. The cellulose is impregnated with insulating oil. The chemical bounds within oil and cellulose molecules can break if the insulation is overstressed by high temperature or electric discharges. In that case new molecules will be created and that generates a variety of gasses that dissolve in the surrounding oil. (Sparling & Aubin 2007:1.) Figure 10 provides an overview of the chemical structure of insulating material and degradation secondary products.

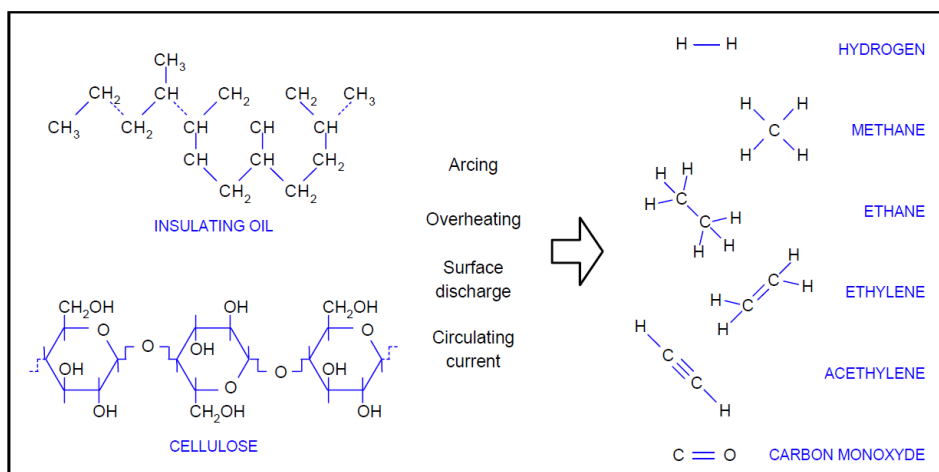


Figure 10. Chemistry of insulation degradation (Sparling etc. 2007:2).

According to Sparling etc. (2007:2) all developing problems in the winding insulation, in the connections, in the core or in the shields will generate a localized spot of high temperature or electric discharges. Those result decomposition of oil and/or paper. Source continues that different gasses are generated depending of the type and severity of the fault. According to Serveron (2007) all fault types are indicated by a variety of gases and not with just one individual gas. See Table 5 for details. This is also confirmed by Duval (2006: 3).

Table 5. Produced fault gasses by failure causes (Serveron 2007).

INDICATION / FAULT GAS	CO	CO ₂	CH ₄	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	O ₂	H ₂	H ₂ O
Cellulose aging	●	●							●
Mineral oil decomposition			●	●	●	●		●	
Leaks in oil expansion systems, gaskets, welds, etc.		●					●		●
Thermal faults – Cellulose	●	●	●				●	●	
Thermal faults in Oil @ 150° C - 300° C			●		TRACE	●		●	
Thermal faults in Oil @ 300° C - 700° C			●	TRACE	●	●		●	
Thermal faults in Oil @ >700° C			●	●	●			●	
Partial Discharge			●	TRACE				●	
Arcing			●	●	●			●	
Guidelines for surveillance range ¹ for Type 1 transformers (IEEE PC57.104 D11d)	N <350 C 350 - 570 W >570		N <120 C 120 - 400 W >400	N <2 C 2 - 5 W >5	N <50 C 50 - 100 W >100	N <65 C 65 - 100 W >100		N <100 C 100 - 700 W >700	

¹ppm for Normal (N), Caution (C), Warning (W) – alarm thresholds

Duval (2006: 5) says that there are several diagnostic methods and main methods are:

- The IEEE methods (Dornenburg, Rogers and key gases methods)
- The IEC ratio codes
- The Duval triangle

According to Duval (2006: 5) methods have different approaches for analyzing the oil. Gas ratios like CH₄/H₂, C₂H₂/C₂H₄ and C₂H₄/C₂H₆ are compared by the Dornenburg, Rogers and IEC ratio codes methods. The key gas method is based on two or three formed main gases. The Duval Triangle depends on the relative proportions of three gases (CH₄, C₂H₄ and C₂H₂). According to same source one disadvantage of the gas

ratio methods is that some results of analysis may be outside the ratio codes and diagnosis is impossible to give (unresolved diagnoses). Duval (2006:5) says that this does not happen with the Duval triangle method as it is a closed system instead of an open one. (Duval 2006:5.)

Serveron (2007) have presented a comparison between different methods and the results are in Table 6. Data for the evaluation was from IEC data bank of inspected transformer failures and other reports.

Table 6. Evaluation of main diagnostic methods (Serveron 2007: 10).

	% Correct Diagnoses	%Unresolved Diagnoses	% Wrong Diagnoses
IEEE Key Gas Method	42	0	58
IEEE Rogers Ratios	62	33	5
Doernenburg Ratios	71	26	3
IEC Basic Gas Ratios	77	15	8
IEC Duval Triangle	96	0	4

Dissolved gas analysis is kept as best on-line monitoring method at the moment as mentioned in chapter 3.2. It can be very effective to detect quickly evolving faults so the sensitivity is very good. Downsides are more related to measurement devices, which are handled in chapter 4.5.2.

4.4.5. Moisture monitoring

According to Davydov & Roizman (2002: 18) the term moisture in the transformer industry is used to indicate absorbed water in the paper or dissolved in the oil. Source continues that the alternative terms for moisture are water or water content. Davydov etc. (2002: 18) mentions that moisture can exist in different parts of the insulation system in a power transformer. Possible spots for moisture are solid insulation, be

dissolved in oil or be found in the form of liquid water at the core or bottom of a transformer (Davydov etc. 2002: 18).

Water may get mixed with the oil by leaking gaskets, poor handling techniques or from the product of insulating paper and oil degradation. As the paper degrades, it produces carbon dioxide and water and as the insulating oil ages, water, acids, sludge and other polar compounds are formed. So its presence is inevitable during the normal service life of a transformer. (Energy Services International.)

As explained earlier the moisture movement between the solid insulation and oil depends mainly on loading and temperature. Virtanen (2009a) mentioned during interview that it is important to know the moisture level in insulation but it is very difficult to measure moisture directly from insulation. For this purpose there is an equilibrium curve which presents the moisture in solid insulation as percentage value. The charts have two parameters, which are temperature and moisture in oil. Du (1999) have studied and compared several different curves. Their conclusion is that all curves differ from measurement techniques, data sources and generating methods. That leads to a situation that caution should be taken when using any of the curves. Their claim is that Oommen's curves match best against the experimental data. See Figure 11 for an example of Oommen's curves for moisture for a paper-oil system. Oommen, Thompson & Ward (2004) says that these curves are unreliable as there are several problems that are:

- Thermal equilibrium is rare
- Moisture distribution in insulation is uneven
- Type, grade and age of oil

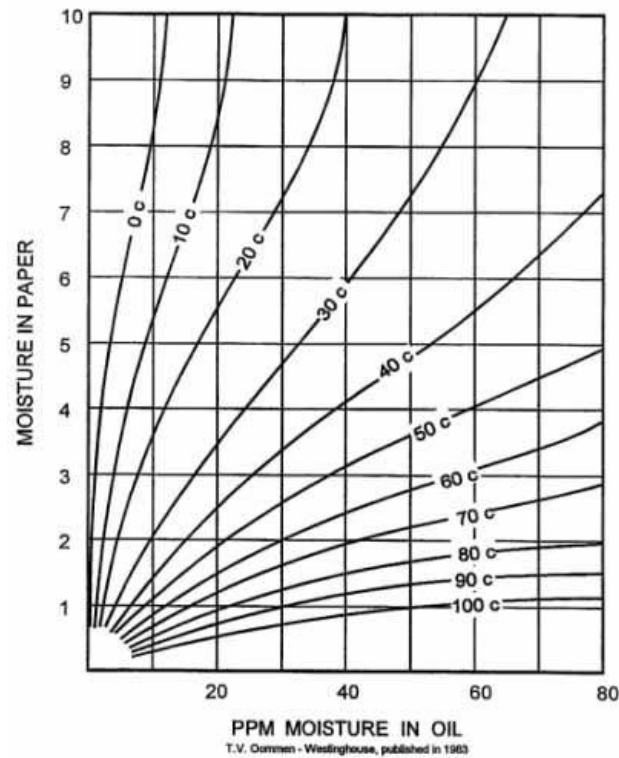


Figure 11. Oommen's curves for moisture equilibrium for a paper-oil system (Du 1999).

Unreliability seems to be known problem as there are proposed solutions for the problem from different sources like Oommen etc. (2004) and Zhou etc. (2009). These proposed solutions are not covered in this thesis.

In general it can be said that moisture is important part of transformer monitoring. It is easy to handle automatically with right sensors but there are challenges with reliability.

4.4.6. Bushing monitoring

Lord etc. (2007: 8) claims that tangent delta method can be used for monitoring current flows through bushing. According to Lord etc. (2007: 8) it is best to determine the health of a bushing is by measuring the current that flows through the bushing insulation. This should be done at full system voltage. Lord etc. (2007: 8) says that in healthy bushing this current is mostly capacitive with minor resistive component. The resistive current will cause heat losses in the dielectric of the insulation material.

According to Melo etc. (2008), one technique for tangent delta monitoring is using the vector sum of the leakage current. This is measured for the three bushings in a three-phase system. The three leakage currents are out of phase by approximately 120° . Usually leakage currents have the same magnitude. In ideal world all three bushings have similar capacitances and the voltages for the three phases are close to balanced. It means that the sum of the three leakage currents (I_{sum}) is much smaller than any of the leakage currents taken individually and this is seen in Figure 12 (a). If there is a change in the capacitance and in the dissipation factor of the bushing on phase A, then leakage current on phase A also changes, as shown in Figure 12 (b). The change vector that expresses the displacement of current I_a from its initial value to its final value is also reflected in the sum current.

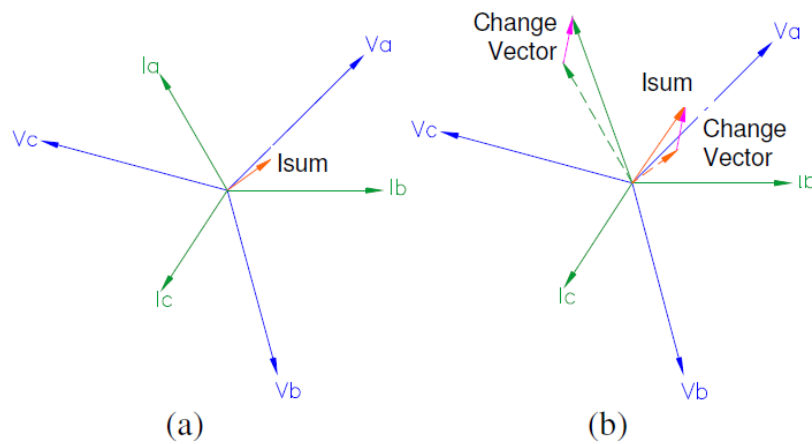


Figure 12. Leakage currents in the three bushings of a three-phase system and their sum; (a) for a given initial condition; (b) with change to the capacitance and dissipation factor for the phase A bushing (Melo etc. 2008: 3).

Change vector is then compared to the sum current (I_{sum}) and this way the changes are detected which occurs in the impedance of the bushing. The method has some specific characteristics and those are:

- An initial reference must be determined for the system's currents
- Absolute values of capacitance and tangent delta of bushings are not measured, only variations occurred in these parameters are measured. Once each bushings

initial capacitance and tangent delta values are known (values present at the moment that the initial reference currents are determined for the bushings), measuring their variations, allows current values to be calculated for capacitance and tangent delta;

- For new bushings, rated values for capacitance and tangent delta supplied by manufacturer of the equipment on the plaque can be used as the initial reference values.

According to Virtanen (2009a) bushing monitoring solutions are still very expensive which means tens of thousands in euros.

4.5. Measuring devices for power transformer condition monitoring

On line measurements gives the data for condition monitoring and for that measurement devices and sensors are needed. In this chapter few measurement devices types are introduced as an example.

4.5.1. Transformer condition monitoring device

There are devices on the market, which handle transformer condition monitoring. Usually these devices collect measurement data from several sensors, process the data and present the information for the maintenance personnel. Measurement methods might have some differences but the output and functionality from the device is very similar. As an example following monitoring functionality is usually seen in transformer condition monitoring device:

- Oil temperature
- Hot-spot temperature
- Load
- Currents
- Gas and moisture in transformer oil
- Cooling control & monitoring

- Oil levels

As an example ABB provides transformer condition monitoring device called TEC (Transformer Electronic Control). The functionality is similar to the list above and also some other functions are available. As an example TEC has tap changer monitoring. Device has eight 4-20 mA, four Pt100 and twelve binary inputs. Additional input for tap changer position is also included. TEC has three binary outputs for alarms. (ABB 2008: 1.) This means that it is possible to attach external sensors to the device. TEC can communicate with upper level devices via OPC or XML files (ABB 2008: 1).

It is worth mentioning that TEC is quite extensive device and it is a good starting point for transformer condition monitoring. One major defect is that the system is completely external to transformer protection systems which are mandatory and this means higher costs (more devices, more complex installation and usability suffers). The functionality itself is enough for these kinds of devices but it should have tighter integration to other systems.

Another example is from Areva. They have several devices for transformer monitoring. These systems are also very extensive with modeling algorithms (Areva 2008). Price is very high for Areva systems. For example overall costs for monitoring device MS 3000 can be around 100000 euros. (Ojanen 2009.)

4.5.2. Dissolved gas analysis device

According to Cargol (2005: 2) dissolved gas analysis can be made with several different methods and devices are divided into two groups. These groups are combustible gas monitors and complete multi-gas monitors. Combustible gas method is rather old technique and depending on manufacturer, the sensitivity to different gases varies (Cargol 2005: 2). The important note here is that the sensor will report only one reading indicating the amount of gasses in the oil. Cragol (2005: 3) continues that Multi-gas method is much recent technique and this one also has differences between manufacturers (Cargol 2005: 3). The principle is to give individual reading for each one of the measured gasses.

Hydran M2 is an example of combustible gas monitor. It is designed and manufactured by General Electric to analyze transformer oil in real time. Device monitors gas and moisture concentration from transformer oil. Hydran M2 is broadly sensitive to combustible gas. This means that a high content of acetylene and low hydrogen content can give the same reading as a low acetylene and high hydrogen. These different conditions cannot be easily resolved only with Hydran M2. (Cargol 2005: 2.)

Device can work as an independent condition monitoring unit or the measurement data can be transferred to another device. The data can be transferred by using 4-20 mA output. With optional communication card it possible to get four 4-20 mA inputs or four 4-20 mA outputs. Technical specification sheet (General Electric 2003) tells that it is possible to transfer sensor oil temperature, gas ppm, oil ppm and relative humidity % with 4-20 mA outputs. For 4-20 mA inputs it is possible to use for example temperature sensors. Communication can also happen with serial communication. Supported protocols are for example Modbus and DNP 3.0. According to Finnish importer of Hydran M2 (2009) the lifetime for the sensor unit is between eight and fourteen years and comments during interviews indicated even shorter lifecycle. The device itself costs around 8000 euros and replacing sensor unit costs around 1500 euros.

Kelman Transfix is an example of a multi-gas monitor. The device can measure eight gases and moisture. The analyzer is based on photo acoustic spectroscopy. The method is rather new in transformer monitoring but the technique is common from other industries. (Cargol 2005: 4.) Biggest disadvantage for the device is price, which is around 35000 euros commissioned. This applies to all full scale multi-gas monitors.

Kelman has also developed a limited version of Transfix that is called Minitrans. This device will measure three gasses and moisture. It is possible to detect critical arcing activity, general fault activity and rapid cellulose degradation. (GE Energy 2009.) Price is much lower as it is around 11000 euros commissioned.

Kelman products support wide range of communication protocols like Modbus, Modbus/TCP, DNP 3.0 and IEC 61850 (GE Energy 2009: 2). IEC 61850 protocol support is a great asset as it has important role in substation world.

The biggest downsides at the moment with dissolved gas analysis are related to the measurement devices. These problems are high price and the technical problems. According to Ojanen (2009) biggest problems are lifetime of the sensors and reliability of information. With multi-gas monitors the experience is quite limited at the moment and some problems, such as false alarms are noticed. It seems that sensor technology has longer lifetime but reliability of the devices is questionable. The results from questionnaire indicate that simple gas analyzing sensor would be preferred by several stakeholders. In other words it means that stakeholders are seeking a simple sensor, which would indicate evolving faults and costs would be reasonable. Of course reliability and lifetime should be good-enough. At the moment it is not possible with current devices but this should be the direction of the development.

4.5.3. Moisture measurement device

Davydov etc. (2008: 18) says that polymer relative humidity and polymer relative saturation sensors are frequently used to evaluate water content in oil. Source continues that absolute moisture content expressed in parts per million (ppm) can be determined by measuring the relative saturation of oil. The water solubility characteristic for the specific oil must be known in advance for this method (Davydov etc. 2002:18).

Daydov etc. (2008: 21) claims that several parameters effects measuring process of moisture assessment in a paper-oil insulation system. These are oil type, age and flow rate. Source continues that also sensor positioning has an effect to the accuracy of moisture assessment. Davydov etc. (2008: 21) says that water solubility in oil is required that installed moisture sensor can be calibrated. According to source water in paper activity was as is one factor when determining dryness in a power transformer.

As an example Vaisala Humicap MMT318 is a moisture measurement sensor for transformer monitoring. The MMT318 measures moisture in terms of the water activity and temperature. The calculation of water content in PPM is an option when the sensor is used with mineral transformer oil. It is also possible to get the transmitter with a ball valve set that enables insertion and removal of the moisture probe without having to

empty the oil system. The MMT318 has two analog outputs and an RS232 serial output as communication interface. (Paasimaa 2003) Price for one sensor is around 2000 euros.

According to experts (Virtanen 2009a, Ojanen 2009) moisture measurement is not kept very important in Finland. This is because climate is very good for transformers and moisture doesn't cause that many failures. The problem with moisture measurement is its measurement location. It should be measured directly from insulation paper rather than oil. Measurement through oil doesn't give reliable results as explained earlier in chapter 4.4.5.

4.5.4. Partial discharge monitoring device

Partial discharge monitoring is fairly new monitoring method and especially as an automated condition monitoring method for power transformers. These devices usually record measurement information from sensors. The sensors can be for example ultra high frequency type.

One example of partial discharge device is manufactured by Doble and it is called TransformerGuard. According to TransformerGuard brochure (Doble 2009) the system is designed for continuous partial discharge monitoring of high voltage equipment like generators, motors, and power transformers in the conventional range of frequency. The device supports four inputs and it can transfer the data outside through TCP/IP protocol. Monitoring device also supports UHF antennas so it can record partial discharge activity with range from 100 to 1000 MHz.

4.5.5. Vibration measurement device

Vibration monitoring is very common with rotating machines condition monitoring. For transformer monitoring it is a relatively new method to monitor the condition. Different types of accelerometers are used for vibration analysis. Garcia, Burgos & Alonso (2006b) have used piezoelectric charge accelerometers for the measurement of vibrations. According to Sanz-Bobi, Garcia-Cerrada, Palacios, Villar, Rolan & Moran (1997) charge type accelerometers cause less electrical noise than integrated circuit

piezoelectric (ICP) type accelerometers. Garcia etc. (2006a) claims that their model calculates how the transformer tank should vibrate if it was healthy. The model compares the calculated and measured vibrations. Then it determines if something unusual is happening inside the transformer. Other option is to measure the vibration and compare it to the fingerprint measurement that is made at the transformer factory.

Both of these methods needs post processing of the measurement data and at the moment there is no suitable device available for the purpose. The amount of accelerometers varies between different studies. The minimum amount of sensors was three and maximum amount of sensors was twelve.

As an example SKF creates accelerometers for machine monitoring and these could be used for transformer monitoring. SKF Machine Condition Transmitter (MCT) collects measurement data from accelerometers, processes the data and sends it forward in wanted format, e.g. 4-20 mA format. One transmitter can handle only one sensor. MCT products have different versions for speed, vibrations and temperature. (SKF 2008.)

4.6. Evaluation of transformer condition monitoring methods

All monitoring methods have their own characteristics with pros and cons. As an overview it can be concluded that temperature and moisture monitoring are most suitable for long-term monitoring and it means monitoring the aging of a transformer. Dissolved gas analysis, partial discharge, vibration analysis and tan delta analysis are suitable for both long and short term monitoring. With short term monitoring, the quickly evolving faults are included.

Transformer condition monitoring is a very wide subject to handle and for that reason an evaluation is necessary to have. The goal for the evaluation was to have a good overview about different monitoring methods where existing measurement devices are included. For this purpose each monitoring methods was ranked in eight different categories. These eight categories were included in two different top level categories. The top level categories are fault detection and other parameters. Fault detection level

included insulation faults, operation faults, mechanical faults and bushing faults. Other parameters included price, reliability, post-processing and reaction time. Categories were defined in following way:

- Price – This category ranks the price level of equipment when investing on condition monitoring system. This does not include any operating or maintenance costs of the system. Prices are received from different device manufacturers like Doble, Kelman and Vaisala. It is obvious that prices are not the whole truth of real price levels but those give a good base to rank different methods. Price levels were distributed between different rankings such way that the resulting distribution between different methods would be quite even.
- Reliability – Category estimates how reliable measurement results are in general. The same figure also estimates the lifetime of sensor unit.
- Post processing – This estimates how much work is needed to post-process measured values and if human expertise is needed.
- Reaction time – Reaction time indicates how sensitive method for changes in transformer health. In other words, is method only able to show long-term changes or does it detect fast changes transformer health. Long term changes are weakness and possibility to quickly react to evolving faults is an advantage.
- Insulation faults – This estimates how well the method can detect insulation failures within transformers and accessories.
- Mechanical faults – This estimates how well the method can detect mechanical faults like winding displacement or core faults.
- Operation faults – This estimates how well the method can detect operation and improper maintenance based faults. This only includes overloading and improper maintenance like cooling problems.

All categories have possible value from one to five where five is real advantage and one is major weakness. Three is either neutral or there is no strong background to make estimation. For price category ranking is based on prices. See Table 7 for ranking values in different categories.

Table 7. Ranking for different categories.

Rank	Insulation faults	Mechanical faults	Operation faults
1	Major weakness	Major weakness	Major weakness
2	Minor weakness	Minor weakness	Minor weakness
3	Neutral	Neutral	Neutral
4	Minor advantage	Minor advantage	Minor advantage
5	Major advantage	Major advantage	Major advantage

Rank	Bushing faults	Post processing	Price range [€]
1	Major weakness	Major weakness	>40000
2	Minor weakness	Minor weakness	20000-40000
3	Neutral	Neutral	5000-20000
4	Minor advantage	Minor advantage	1000-5000
5	Major advantage	Major advantage	0-1000

Rank	Reaction time	Reliability
1	Major weakness	Major weakness
2	Minor weakness	Minor weakness
3	Neutral	Neutral
4	Minor advantage	Minor advantage
5	Major advantage	Major advantage

The ranking in different categories are based on writer's personal estimate which is based on all interviews and literature survey. As results are mainly based on opinions, it means that results must be interpreted quite critically. The goal was mainly to give overview of different monitoring method for the writer but also to encourage reader to create own overview of the current situation. Results are gathered in Table 8 for each monitoring method. The results show big variances between different methods and comparing different methods is difficult from regular table. Appendix 2 includes radar charts to give easier way to interpret results and charts are based on data in Table 8. Average values were calculated for both top level categories. Also total average was calculated from top level category averages. Figure 13 shows bar chart for each calculated average.

Table 8. Evaluation of monitoring methods.

Method	Insulation faults	Mechanical faults	Operation faults	Bushing faults	Average of fault detection	
Thermal	2	1	4	1	2	
Moisture	2	1	4	1	2	
Vibration	1	4	2	1	2	
Partial discharge	5	2	3	1	2,75	
DGA (Multi-gas)	4	2	3	1	2,5	
DGA (Combustible gasses)	3	1	2	1	1,75	
Tan delta	1	1	1	5	2	

Method	Reliability	Price	Post processing	Reaction time	Average of other parameters	Total average
Thermal	4	5	5	1	3,75	2,875
Moisture	4	4	4	2	3,5	2,75
Vibration	3	3	1	4	2,75	2,375
Partial discharge	3	1	2	5	2,75	2,75
DGA (Multi-gas)	3	2	3	4	3	2,75
DGA (Combustible gasses)	1	3	4	3	2,75	2,25
Tan delta	3	2	2	3	2,5	2,25

From fault detection figures it can be seen that none of these methods are covering all fault detections perfectly. Partial discharge and dissolved gas analysis are best options to cover different types of faults. Other methods are specifically meant for one failure type. It also needs to be mentioned that Tan delta method is very good for bushing monitoring but it doesn't cover any other faults.

Other parameters on the other hand show that better monitoring capabilities results high price, demanding post-processing or even both. For example temperature monitoring has limited monitoring capabilities but on the other hand it is very cheap and reliable method. As an opposite example multi-gas dissolved gas analysis is very expensive but extensive monitoring method.

If averages are studied from Figure 13, it is possible to say that total averages are quite close to each other with all monitoring methods. A more interesting note about the total averages is that none of these methods have total average above 3. Average values for

top level categories shows that there are major differences between monitoring methods. As an example fault monitoring average for thermal method is only over 2 but other parameters are 3,5. For partial discharge it is just the opposite.

The conclusion from evaluation is that proper condition monitoring needs several methods instead of only one. It also seems that there are several monitoring options for different transformer applications.

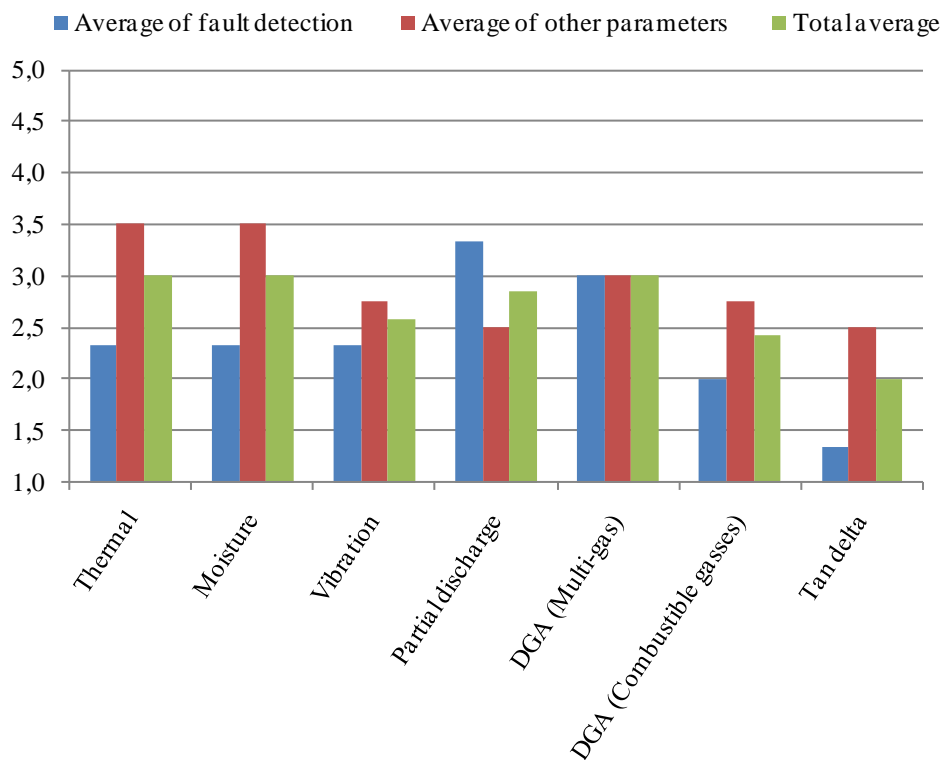


Figure 13. Average values for monitoring method.

5. POSSIBILITIES OF ON-LINE MONITORING

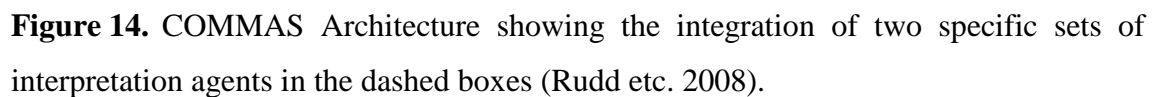
This chapter covers possible development subjects which could be used to improve condition monitoring in the future. Collecting the data is one part in condition monitoring and other parts are diagnosis and prognosis. Following sections are mainly related to the last two parts of condition monitoring.

5.1. Transformer predictive aging model

Prediction of the aging is one possible direction for transformer condition monitoring. There are two examples quite close to each other, so this could be a possible feature to be implemented in transformer monitoring system. First one is related to diagnosis and the second one is related to prognosis. These two examples are presented in the following.

5.1.1. Condition Monitoring Multi-Agent System (COMMAS)

Rudd, etc. (2008) claims that an accurate transformer condition diagnosis would include many different data interpretation methods. They continue that most complete picture of transformer health is achieved with multiple types of sensor. They also mention that such a system requires a way of integrating different components, allowing sensors and interpretation techniques to be easily added and removed from the diagnosis process. Their solution for this is agent technology, where individual autonomous agents encapsulate different tasks. Figure 14 shows how agents would interact between each other to define transformer health.



Bajrachary, Koltunowicz, Meijer, Djairam, De Schutter & Smit (2009) proposes a health state prediction model to evaluate and predict aging of a transformer. The model predicts the future health state of the transformer based on the historical and present condition data.

According to Koltunowicz etc. (2009) the condition analysis incorporates the operating condition such as load, voltage, temperature and other monitoring data like results of partial discharge measurements. The monitoring system gives an indication of the present health state of the transformer. Any previously implemented or future management actions to improve the health state such as maintenance schemes are also considered in the model. The schematic of health state prediction model is presented in Figure 15. (Koltunowicz etc. 2009: 3-4)

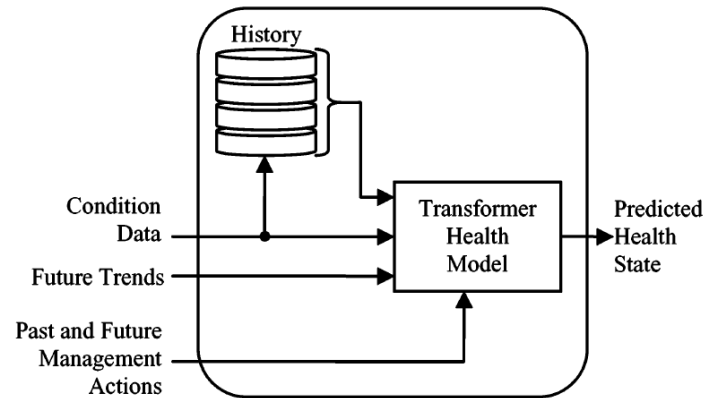


Figure 15. Health state prediction model for a transformer (Koltunowicz etc. 2009: 3-4).

The proposal of Bajrachary etc. (2009) also includes an optimization model for maintenance and it is presented in Figure 16. According to the source the optimal maintenance action balances the economical cost of the maintenance, the improvement of the health state, and the reduction in the failure rate of the equipment. Their optimization model uses the predicted health information to identify the required maintenance actions. Bajrachary etc. (2009) mentions that the model considers three different cost functions, while evaluating the performance of each of the actions provided by predictive health model. These three are usage and maintenance actions, cumulative stresses and failure rate, as shown in Figure 16. The usage and maintenance actions include the economical cost of the maintenance. The failure rate includes the cost associated with the failure of the equipment. The cumulative stresses take into account the cost of deterioration of the equipment. Bajrachary etc. (2009: 2) According to Koltunowicz etc. (2009: 4) the health state prediction model is also used to verify the effect of optimized actions on the health.

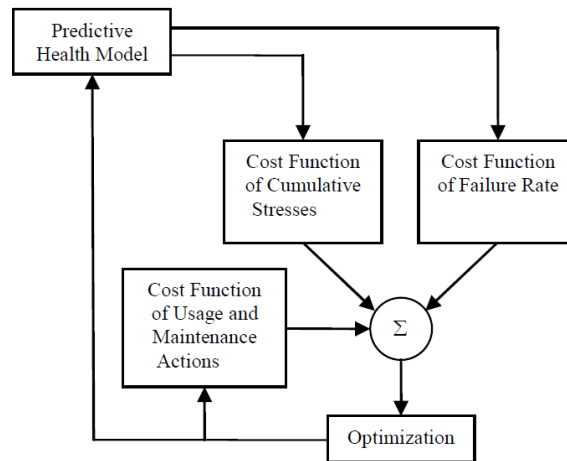


Figure 16. Optimization of maintenance (Bajrachary etc. 2009: 3).

5.2. MIMOSA standards

Lack of standards was mentioned in the results of the questionnaire and its effect on slowing down the development of on-line condition monitoring. MIMOSA standards are introduced here as an example of a monitoring standard, but it is not commonly used among the industry.

MIMOSA is an alliance of Operations & Maintenance (O&M) solution providers and end-user companies who are focused on developing consensus-driven open data standards to enable Open Standards-based O&M Interoperability. Mimosa has two different standards, which are OSA-EAI and OSA-CBM. (Mimosa 2009.)

The MIMOSA OSA-EAI is a standard for data exchange of engineering asset management data. Interconnectivity of the islands of engineering, maintenance, operations, and reliability information is embodied in MIMOSA OSA-EAI specification. The "information network" is constructed by using OSA-EAI bridges to proprietary data stores to allow this information to be easily understood and utilized. (Mimosa 2009.) Figure 17 shows the architecture and components of MIMOSA OSA-EAI standard.

According to Mathew, Zhang, Zhang & Ma (2006) the MIMOSA OSA-EAI is a thorough and well constructed specification for asset management data. The CRIS (Common Relational Information Schema) provides a usable database implementation that can be populated by a comprehensive reference data set. With a few adjustments, the OSA-EAI is suitable for a condition monitoring database, covering the major aspects of condition monitoring, including asset and sensor registry management, measurement event management and storing raw and processed signals. The primary issues encountered for condition monitoring system development were the lack of documentation and the complexity of the data model. Peculiarities also arose in the reference data and certain sections of the data model. To support advanced trending and diagnostic functionality, additional tables were required. Although the MIMOSA OSA-EAI continues to be a work in progress, it provides a bright future for engineering asset management systems. (Mathew etc. 2006.) Referred review is over three years old so the situation with documentation might have changed in the last years. According to the history data Mathew etc. (2006) have used version 3.0 of the specification. At the moment valid version is 3.2.2.

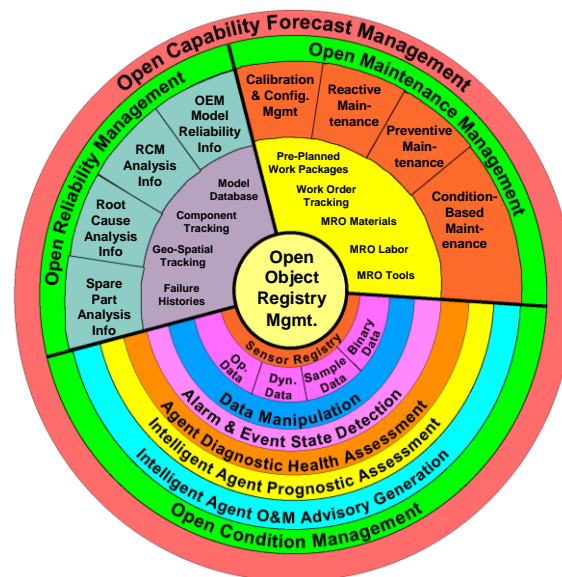


Figure 17. MIMOSA Open Systems Architecture for Enterprise Application Integration (OSA-EAI) (Mimosa 2009).

The OSA-CBM specification is a standard architecture for moving information in a condition-based maintenance system. OSA-CBM specifies a standard architecture and framework for implementing condition-based maintenance systems. Standard describes the six functional blocks of CBM systems, as well as the interfaces between those blocks. The standard provides a means to integrate many disparate components and eases the process by specifying the inputs and outputs between the components. Basically it describes a standardized information delivery system for condition based monitoring. It describes the information that is moved around and how to move it. It also has built in meta-data to describe the processing that is occurring. (Mimosa 2009.)

These standards could evolve to the point where those are accepted by the industry. At least these standards would give a good base to start developing industry approved standard. OSA-EAI seems to be more useful from electrical system point of view. IEC 61850 has a strong position in substation and edition 2.0 of the standard gives more options for condition monitoring. Communication between devices is in good shape because of IEC 61850 and this means that OSA-CBM is more or less useless. On the other hand OSA-EAI covers the communication between power plants and maintenance centers. It would make sense to study this standard more. As an example power plant maintenance personnel might not be experts analyzing electrical failures and then analysis should be done by external partner. Experts might be located in other parts of the world. Standardized data transfer protocol enables opportunities to develop condition monitoring. For example various experts can quickly reach data from various locations to solve problems.

5.3. Integrating monitoring framework to secondary system

One possibility to develop condition monitoring and to limit possible costs is to integrate the condition monitoring functionality to existing secondary system. Transformer protection relays and terminals are always mandatory even if there is high range condition monitoring and maintenance system connected to the transformer. This increases the overall price for whole secondary system. There are also communication

protocols like IEC 61850 which are field proven and even have support for condition monitoring. Some protection relays already have condition monitoring functionality implemented and most likely the functionality will increase in the near future. The major defect is related to data presentation. Either information value is low or finding the correct information is difficult.

Secondary system is usually having protection relays, communication gateway, instrument transformers, backup power supply and wiring. The idea is that protection relays would gather and measure the data for condition monitoring. Then the pre-processed information would be transferred to station automation device, which also works as a communication gateway. Station automation device would present processed information about transformer health with proper user interface or the data would be sent forward. Figure 18 shows an example structure of existing secondary system in power plant.

The combination of relay and station automation device should actually be a framework for condition monitoring, which is expandable with new features. As mentioned earlier the general opinion is not encouraging to use condition monitoring. Framework solution would allow customers to buy basic framework first together with protection relays, which could be expanded if better monitoring is needed.

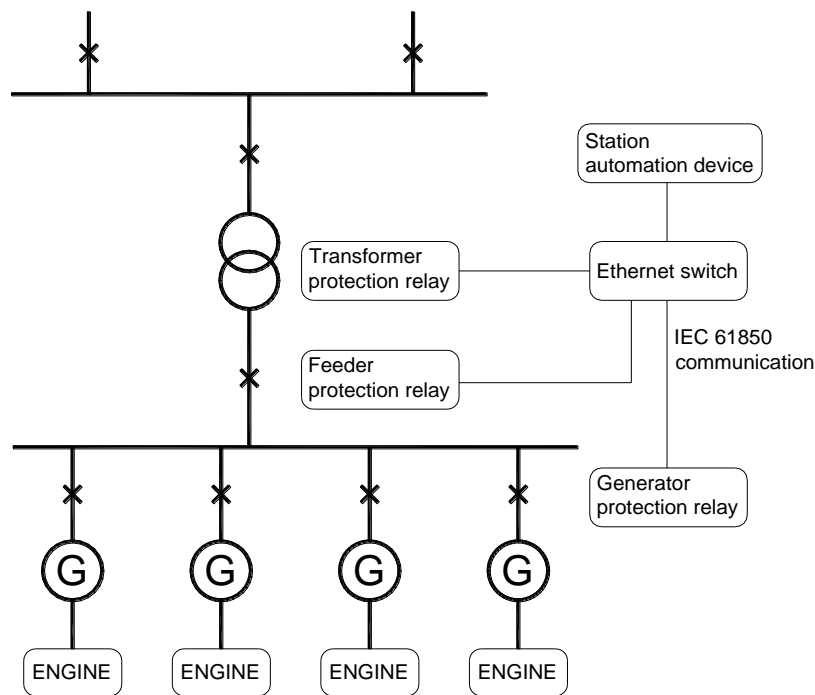


Figure 18. Typical secondary system in power plant.

Next sections will introduce transformer protection terminal and station automation device and current capabilities of these devices.

5.3.1. Transformer protection terminal

High-end transformer protection relays have extensive functionality and these devices could be used as measurement data nodes, which collect the data from sensors and send it to a higher level, e.g. station automation device. Protection terminals' main purpose is to protect the transformer with appropriate functionality. With today's technology, also control, measurement, and condition monitoring functionality can be included in the same device. Normally, protection terminals have a flexible I/O interface and there are usually 4-20 mA inputs available as an option. This way, both position indication and measurement information can be gathered into one device. At the moment, there are several manufacturers that provide this kind of devices.

As an example, RET 54_ is a transformer protection terminal manufactured by ABB. The device can also run other than protection functions. The device has some functionality for

circuit breaker and secondary system condition monitoring. (ABB 2005.) It is important to notice that the device has a weak point, which is lack of direct functionality for transformer condition monitoring.

It is possible to add RTD/mA card to the device. This means that relay has 4-20 mA and Pt100 inputs. This gives possibilities to use external sensors and gives the possibility for transformer condition monitoring. One big asset of the RET 54_ is the communication possibilities to upper level devices. With use of PLC logics it is possible to combine data from different sensors. With the help of this information alarms and warnings can be sent. (ABB 2005.)

5.3.2. Station automation device

Station automation device is normally located in a substation and its main purpose is to act as a communication gateway. With existing technology, other functionality can be added to the device. One example of this is to include data logger to the station automation device. Normally these devices have user interface to monitor the data provided by substation IEDs (intelligent electronic device).

COM600 is an example of station automation device manufactured by ABB. It can work as a communication gateway, automation platform and user interface solution for power plant. The gateway functionality provides connectivity between substation protection terminal and other IEDs. The gateway also connects network-level control and management systems. It has optional web browser based user interface. (ABB 2009: 13). Figure 19 shows a conceptual view of COM600 device. The figure presents the structure how data is transferred between different interfaces.

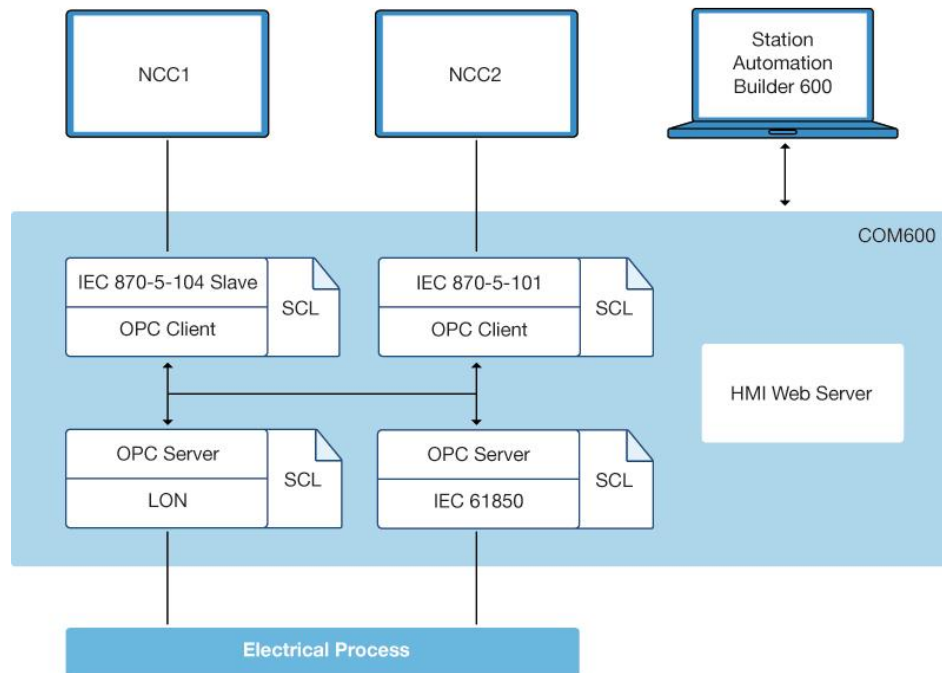


Figure 19. Conceptual view of station automation device COM600 (ABB 2009: 15).

6. INITIAL PLANNING OF CONDITION MONITORING SYSTEM

This chapter defines the requirements for the condition monitoring system. First some limiting factors from stakeholders are introduced.

6.1. Limiting factors in power plant environment

In the introduction it was stated that the condition monitoring system should be usable in power plants and this gives some limiting factors which needs to be taken into account when designing the system.

6.1.1. Good enough level for transformer condition monitoring

Hypothesis defined that condition monitoring must be in good-enough level. The term in this case means that system should indicate specified faults reliably before the failure. The exact origin and root cause for early fault are only secondary objects. In other words analyzing and prognostics are not in the focus area.

6.1.2. Price factors

Cargol (2005: 1) claims in his article that most utilities are willing to spend up to 5 % of the cost of a transformer on monitoring equipment. This was confirmed by interviews and claim works as a good base for the research. Important aspect in this claim is that electric utilities are not willing to spend fortunes on condition monitoring.

In Wärtsilä power plants the transformers varies 50 to 120 MVA and average price for 50 MVA transformer is around 600 000 euros (Virtanen 2009a). Here we can make a conclusion that 30 000 euros would be the price limit for the system if the transformer were around 50 MVA. Although some electric utilities mentioned that price should be between 10 000 and 20 000 euros. This gives enough information price factors to be defined as one limiting factor for the research.

Of course 120 MVA transformers are more expensive. It means that one solution for this case is creating for example three levels for the monitoring system. Choice between different systems would depend on the criticality and the size of the transformer.

6.1.3. Devices on the market

Hypothesis defined that condition monitoring system could be achieved with devices which are already on the market. Based on research and discussions with several experts it can be clearly seen that there is large amount of on-line sensors on the market.

Based on the research and discussion it is clear that dissolved gas analysis (DGA)-devices are commonly used for transformer monitoring. Other popular devices are temperature sensors. It is possible to find on-line measurement devices even for more exotic monitoring methods. Some of these devices are introduced in the earlier chapters. In general it can be stated that there is enough monitoring devices and challenges are more related to data presentation and price factors.

6.1.4. Existing condition monitoring services

Some power plant manufacturers already provide condition monitoring services for end users and utilities. Also electric utilities have their own monitoring systems. Due to the lack of standards for this kind of systems and services, the variations can be significant between different stakeholders.

As an example Wärtsilä has created Condition Based Maintenance service for their customers. The service is heavily relying on their condition monitoring system. The data is automatically collected from the site and uploaded to Wärtsilä CBM centre, which is located in Vaasa, Finland. Condition Based Maintenance system monitors constantly engines in ships and power plants around the world. Wärtsilä CBM centre is connected to the engines and it can read the values provided by several different sensors. Measured values will be transferred into a database and from there the values are analyzed and compared to optimal values. Wärtsilä CBM centre is able to give several different recommendations and reports to the customer based on the values

recorded from the engine. These include next maintenance activities and time frame, best operating mode etc. Also the predictability of spare part change is increasing because of stored service reports. (Wärtsilä Finland Oy 2005: 8-11.) Transformer condition monitoring system must be compatible with Wärtsilä's CBM in a way that Wärtsilä is able to include transformer condition data into their reports.

6.2. Market requirements for transformer monitoring system

Requirements are the necessary, needed or demanded features, functions and services product shall provide. Market requirements for transformer condition monitoring system are defined based on the items mentioned earlier in this thesis. Only method for requirement engineering and conclusions are presented in this chapter. More detailed description and listing of the requirements are presented in supplementary material.

As mentioned in the chapter 6.1.2 three levels in condition monitoring should be considered. Requirements are divided into three different product levels, which are basic, middle and high level. These three levels could be considered as a roadmap for transformer condition monitoring system and also as product range for different purposes. These requirements are defined in general level from end user point of view and will not define any technical equipment. These are covered in chapter 7.

In this case the goal is to gather the needs and wanted features to requirements of transformer condition monitoring system. Requirements will be engineered by using requirement abstraction model (RAM) and it divides requirements into four different levels. The levels are strategy, feature, function and design. Only strategy, feature and function level requirements are mandatory at this phase and design level requirements are part of the implementation. All four requirement levels have different definitions which are presented in Table 9. Requirements are also linked together between different abstraction levels. Relations can be many-to-many type.

Table 9. Requirement abstraction levels (Fricker 2008).

Abstraction level	Definition
Strategy	<ul style="list-style-type: none"> ▪ Goals of the company related to the product and its markets ▪ The requirement is about a market goal, a customer or a product portfolio.
Feature	<ul style="list-style-type: none"> ▪ Product features that influence buying decisions and costs for the company ▪ The requirement defines the product interface from a customer value perspective. ▪ May become a part of product marketing ▪ The customer is dependent on the requirement
Function	<ul style="list-style-type: none"> ▪ Requirements related to product usage and observable product properties (quality) ▪ The requirement defines the product interface from a product usage perspective. ▪ Hardware or software that is interacting with the product is dependent on the requirement
Design	<ul style="list-style-type: none"> ▪ Technology, architecture and design decisions for the product ▪ The requirement is a design decision from a product implementation perspective.

Requirements can include several different attributes. This thesis uses following attributes to describe the requirements: ID number, title, description, motivation, priority and RAM level. All these are mandatory to have complete requirements.

As mentioned, detailed listing of the requirements is presented in supplementary material. Table 10 presents an example how requirements are divided into three RAM levels. This example presents only the title and abstraction level of the requirement.

Table 10. Requirements from end user point of view.

Strategy	Feature	Function
	Existing infrastructure is supported	
	Existing Condition Based Maintenance services are supported	All monitoring data is accessible from different CBM systems
		Existing Condition Based Maintenance services are supported
	Existing secondary circuit is possible to upgrade with TCM system	
		Implementation by only changing mandatory framework components

As a result, requirements were defined for three different product levels and requirements were divided into three RAM levels. Conclusion is that product levels are basic, middle and high. All these have different purpose and scope which are:

- Basic level product – Includes framework for condition monitoring and aging monitoring. First step towards complete monitoring solution.
- Middle level product – Additionally to framework and aging monitoring this product includes better fault monitoring and also some control functionality for example cooling control. This provides good fault monitoring and includes most critical components for reliable monitoring.
- High level product – This product includes full monitoring and controlling capabilities. High level product is more or less a complete solution for most critical applications.

7. TECHNICAL SPECIFICATION FOR THE CONDITION MONITORING PILOT PROJECT

Purpose of the pilot project is to gather measurement data and experiences that the next actions with condition monitoring research project can be evaluated. Possibilities of transformer condition monitoring should be evaluated with the help of the pilot project. The limiting factors and requirements must be respected when designing the system for the pilot project.

As the pilot project is a first step towards commercial product, it is decided here that the design should reflect to the purpose of first commercial product. It is also taken into account that the pilot project must be extendable with new sensors which was also defined as a requirement for transformer condition monitoring system. The pilot project should study integration of monitoring framework to secondary system. This means that secondary system will be designed as before and monitoring technology is an additional part of secondary system.

The system design should include all the components what is thought to be included in the first commercial version and additional measurement methods to confirm correct results reported by the system. Second reason for additional sensors is to gather results for research purposes.

It must be remembered that the pilot project is used to test the overall concept and monitoring framework. Total focus should not be in the individual output parameters. Of course new methods (prognostics and diagnostics) and parameters can be added later on when framework itself is approved. This specification will cover only condition monitoring related features and functionality.

7.1. System design

System design will be based on requirements defined in chapter 6.2 and from there it is possible to form an overview picture of the system which is actually very close to

existing secondary system in power plants as seen in Figure 18. If we take the Figure 18 on page 72 and include sensors in to that picture we get the overall design for pilot project. This overview utilizes the usage of relays as data collecting points and station automation device to present and store measurement data of the transformer. See Figure 20 for clarification of the pilot project condition monitoring system. The figure also shows that condition monitoring system framework would be based transformer protection relay and station automation device.

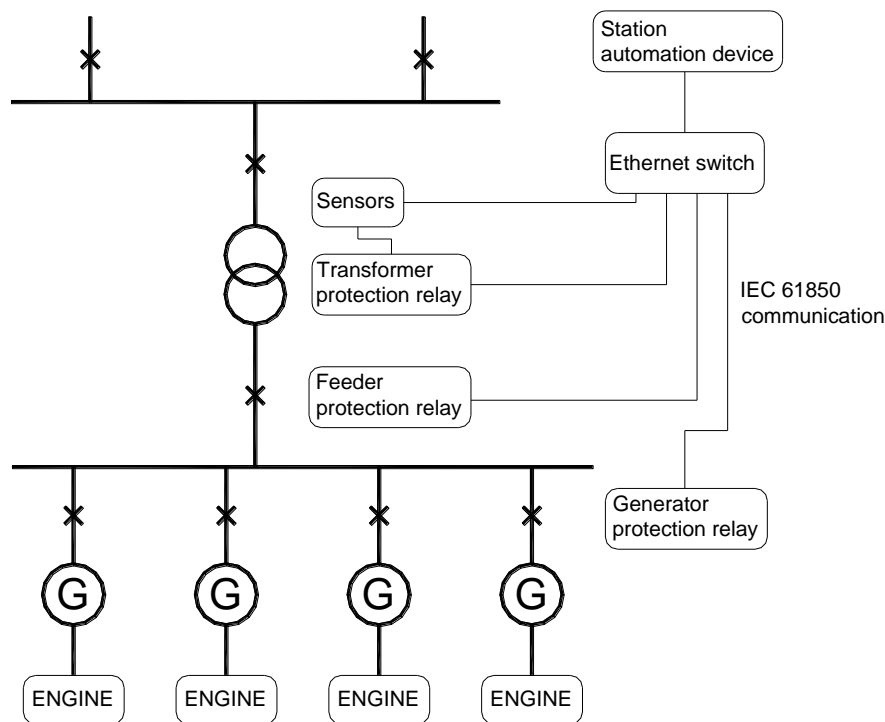


Figure 20. Simplified overview of secondary system for pilot project.

The whole secondary system would be based on IEC 61850 communication protocol. This is not very popular communication protocol in power plants at the moment. Despite that fact IEC 61850 is chosen to be used for secondary system communication protocol as it gives plenty of opportunities and this standard also takes condition monitoring into account. Nowadays majority of new protection relays and other secondary system products support IEC 61850. This also gives enough flexibility for the future. For example IEC 61850-7-4 edition 2.0 brings new possibilities for condition monitoring (IEC 61850-7-4 2009).

7.1.1. Data presentation

The user interface itself is not handled in this chapter. This chapter is more related to different parameters, which are possible to record and to present. Based on the devices used in the pilot project it is possible to show certain parameters directly with the monitoring software. These are mostly related to temperature, moisture, electrical values and oil status. More detailed description about measured parameters is included in Table 11. This table is generated based on the parameters that each measurement device can produce.

Table 11. Measurable parameters.

Parameters	Source
Three phase currents on HV side	RET 543
Three phase voltages on LV side	RET 543
Neutral current	RET 543
Frequency	RET 543
Three phase power	RET 543
Reactive power	RET 543
Energy	RET 543
Residual voltage	RET 543
Transformer tank top oil temperature	Pt100
Transformer tank bottom oil temperature	Pt100
Ambient air temperature	Pt100
Moisture in oil (radiator) as ppm	MMT318
Oil temperature in radiator	MMT318
Hydrogen amount	Minitrans
Carbon monoxide amount	Minitrans
Acetylene amount	Minitrans
Moisture in oil (Minitrans) as ppm	Minitrans
Status of cooling fans	RET 543

Other parameters must be calculated from measured parameters. There are few options and these are presented in Table 12. The long term goal for calculated parameters should be predictive aging model. Diagnosis and Prognosis were not in the scope of this thesis so aging model should not be included in this phase. Calculated values in Table 12 are already well known parameters, which are generally approved by the industry.

Generally approved in this case means that calculated parameters can be found from IEC 60076-7 standard.

Table 12. Calculated parameters.

Calculated parameter	Standard
Hot-spot temperature	IEC 60076-7
Transformer aging	IEC 60076-7

7.1.2. Data storage

It was defined that data storage should be handled in one single repository and in this case the repository is station automation device. Usually transformer age is around forty years so it means that there is a big challenge how the data is secured for such a long time. It is not handled in this thesis but it must be covered in the commercial project.

For pilot project the proposed solution is to store all measurement data into station automation device without any filtering or processing. The capacity should be enough for more than a year of raw data. Daily averages and peak values would be sent to power plant maintenance centre on weekly basis.

7.2. Proposed equipment

Transformer condition monitoring system and secondary system in general needs large amount of devices and most of these are critical for the operation. This chapter will introduce the main components and sensors. Instrument transformers, wirings and auxiliary power supply are not presented.

Figure 21 presents a detailed view of a proposed pilot project system. Diagram shows used equipment and connections between devices as a single line diagram. Detailed specifications of the devices are introduced in following sections.

This solution would support and fulfil the requirements defined in chapter 6.2 for middle level transformer monitoring system.

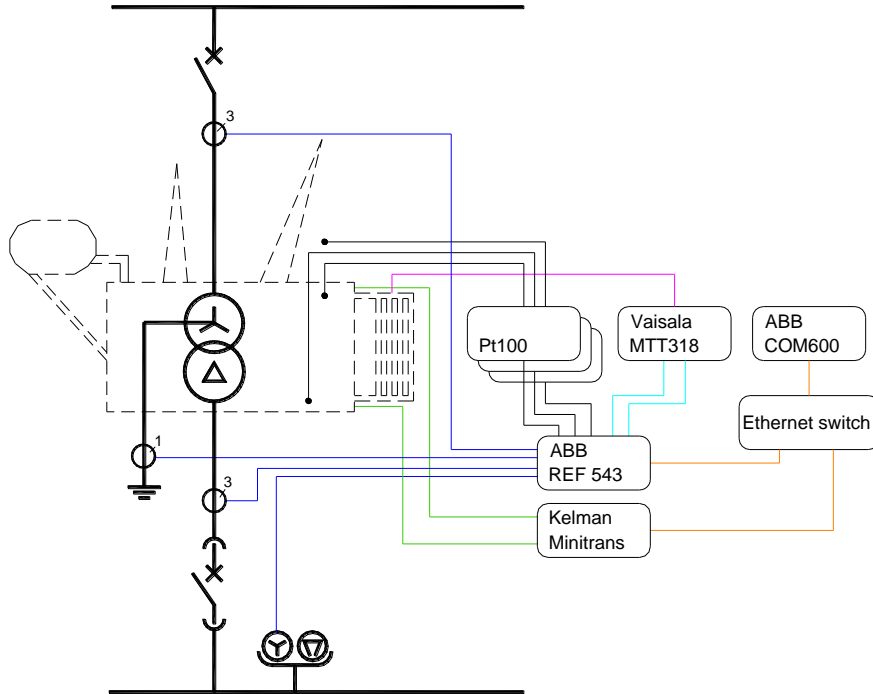


Figure 21. Detailed design of the transformer condition monitoring system for the pilot project.

This system has some overlap in the functionality but this should be acceptable in pilot project. This gives experience how different sensors work in different environments. It is obvious that overlap must be removed for commercial product but not in pilot project phase, especially if stakeholders don't have large knowledge base from earlier projects.

7.2.1. Transformer protection relay

Transformer protection terminal is one of the key components for the system and is part of the monitoring framework. First of all it handles all the protection functionalities and it also handles measurement of certain parameters through RTD-inputs. Relay works as a multiplexer which combines several parameters and then provides the information accessible for other devices, mainly for substation automation device.

Possible choice for transformer protection terminal would be RET 543 manufactured by ABB. The product has the functionality to protect transformer and it has optional resistance temperature detector (RTD) module. RET 543 also supports IEC 61850 through communication converter SPA-ZC 400. Protection relay needs current and voltage measurements and these measurements are also used condition monitoring to monitor currents, voltages and loading. RET 543 includes eight RTD inputs as an option. These inputs should be used for different sensors like three Pt100 sensors and one moisture sensor (reserves two inputs). This still leaves three inputs for later use.

7.2.2. Substation automation device

Substation automation device will collect all measurement information and present it for the maintenance personnel. The device would also work as a server for other systems where those could retrieve processed measurement information. Main purpose for substation automation device would be acting as communication gateway for the secondary system and with needed functionality it would also work as a central device for condition monitoring. These needed functionalities would be data collecting, storing functionality and human-machine interface (HMI) for data presentation. It is assumed that the device is able to handle communication to all directions (towards secondary system and higher level systems)

COM600 manufactured by ABB is the device proposed for this purpose as it has functionality to gather data from other devices in the substation. It supports IEC 61850 and also other communication protocols like Modbus and DNP 3.0. COM600 would be used to record all measurement data collected from transformer protection terminal and other devices. COM600 has eight gigabyte flash memory which gives enough buffer for data storage. It is also possible to get web based HMI for COM600. The device has logic processor and this would be used for alarms. This means that individual sensors or devices would not send any alarms related to condition monitoring. Everything would be handled through station automation device to minimize false alarms.

7.2.3. Temperature sensors

Temperature sensors are commonly used for monitoring applications. The Pt100 sensor should be three wire model and IEC 751 class should be B. These parameters are chosen by the fact that RET 543 supports three wire method. Pt100 sensors are well known and very cost-effective choice.

The accuracy differences between IEC 751 classes A and B are so small below 100 degrees that there is no reason why higher accuracy would be needed. All other parameters are pilot project specific like casing, sensor length and cable length.

7.2.4. Moisture sensor

First of all the moisture sensor must be designed for transformer monitoring. Ppm value is commonly used with transformer moisture measurements so it would be a requirement for the moisture sensor.

One solution for this would be Vaisala HUMICAP MMT318 moisture sensor and transmitter. MMT318 is also designed for transformers and it supports ppm value. The output from the sensor is in 4-20 mA format and the device has two outputs. Outputs are reserved for ppm, temperature and water activity values. Two of these can be active at a time.

7.2.5. Dissolved gas analysis device

Dissolved gas analysis device is best device at the moment to detect quickly evolving faults before failure. As mentioned earlier the problem with dissolved gas analysis devices is pricing. For the pilot project it is enough to use middle range product which would detect three different gases. This would indicate evolving fault but doesn't give exact diagnosis.

Kelman Minitrans is a good option as dissolved gas analysis device. The biggest strength of Minitrans is the support for IEC 61850 so it can be directly connected to COM600.

7.3. Testing methods for pilot project

It was defined that pilot project should test the transformer monitoring concept in general and condition monitoring framework. These two elements are split into smaller parts, which are listed and described below.

- Instrument sensor testing – This includes testing that all sensors give reliable measurement results. Also measurement sensors that are overlapping should be compared.
- Functionality of framework components – Key components of transformer condition monitoring framework are protection relay and substation automation device. First it must be monitored that devices work as specified. Second it should be studied if these components are the optimal devices for framework.
- Data presentation – Data presentation is important for maintenance personnel and their behavior should be followed while they use the system. Data should be presented such way that system users are comfortable using the data presentation and it supports maintenance decisions.
- Economical aspects of condition monitoring – This should be one of the main subjects to study. For end users it is important information to know when it is justified to use transformer condition monitoring from economical point of view.
- Data processing – Processed data should be monitored with regular intervals, so that calculated data is correct and algorithms give reliable results in different conditions.
- Data storing – Data storing should be followed and investigated that what is the most efficient way of storing data for long periods of time and what information to store.

It can be assumed that the pilot project is done with new transformer. This gives the opportunity to monitor life cycle of a transformer right from the beginning.

8. CONCLUSIONS

Power transformers are critical components in electrical networks and especially in power plants. The engines in the power plant might already have condition based maintenance but not the electrical circuit. This was the starting point for the thesis, which studies automated condition monitoring for power transformers. The goal was to achieve concept of good-enough condition monitoring system where costs are decent. In other words the goal was to achieve system, which gives reliable information about transformers condition and investment costs are less than 5 % of transformers overall price.

Research was started by studying goals for transformer condition monitoring. The used sources were literature and questionnaire for stakeholders. Questionnaire was done according to Delphi method. Stakeholders in this case include power plant manufacturer and service provider, electric utilities, and transformer manufacturer. First all stakeholders were interviewed and summary was created based on interviews. The summary was flavored with some provocative opinions. Interviewees reviewed this summary and they gave their new opinions and arguments. After review the summary was modified according to first review round. Then interviewees had opportunity to review it again. Final version of the questionnaire results was based on the comments of review round two. The final summary was included in the thesis. The results show that condition monitoring has problems and big challenges. These problems and challenges are related to devices, knowledge and standards. On the other hand results show that stakeholders are interested about condition monitoring and they see potential in it. When goals from literature and the questionnaire are combined, the conclusion is that traditional maintenance has strong base which is both advantage and disadvantage. As a positive side the need for automated condition monitoring is quite clear and some industries already have experience from automated condition monitoring. On the other hand electrical business is changing very slowly and changing existing ways of working is a long process.

Condition monitoring of power transformer chapter handled the structure of a transformer, aging process of transformer, possible faults and fault statistics, condition monitoring methods and examples of monitoring devices. The conclusion from statistics was that transformer condition monitoring is not justified by fault rate but it is justified when failure expenses are studied. Many of the failures are possible to discover with different monitoring methods. At the moment the most cost effective way is dissolved gas analysis. This handles both aging and quickly evolving faults. Temperature, moisture and loading are useful when aging process in the focus. There are other techniques, which are effective but are not industry proven, commercial measurement devices are missing or price is too high. One example of these is partial discharge.

Some possibilities of transformer condition monitoring now and in the future were also covered. This is divided into three sections, which are predictive aging model transformers, maintenance and condition monitoring standard MIMOSA and secondary system as framework for condition monitoring. Predictive aging model presents options how to have better utilization of monitoring data. These models predict transformer aging by using monitoring data and loading trends. Diagnosis and prognostics are the next step from monitoring where predictive aging models belong. Second section was about standards. In the questionnaire it was mentioned that one major challenge for maintenance and condition monitoring was lack of maintenance related standards. MIMOSA is one option for this and it is briefly introduced as a possible option to be used. Last section was related to monitoring framework. Secondary system is already having some monitoring functionalities integrated to protection relays and there are also solutions for data collecting. Problem is to collect and process the measurement data such way that it is easy to access and costs are acceptable. Integrating monitoring system to existing secondary system could create a proper framework and solution.

Initial planning of transformer condition monitoring system was based on findings in earlier parts of thesis. The initial plan is divided into to two parts, which are limiting factors in power plant environment and market requirements for the system. Limiting factors are mainly defined in hypothesis. Market requirements are a collection and a combination of requirements for transformer condition monitoring system. The

requirements reflect the needs from literature and stakeholders, which are described earlier in the thesis. Requirements were engineered by using Requirement Abstraction Model, which splits requirements to four different levels and three of those were used. The result was that requirements were defined to three different product levels, which could also be kept as a roadmap for transformer condition monitoring system. Basic level includes the monitoring framework with aging monitoring. Middle level includes better fault monitoring and some transformer control functionality added to the basic level. This provides good fault monitoring and includes most critical components for reliable monitoring. High level system includes full monitoring and controlling capabilities. High level product is more or less a complete solution for most critical applications.

Last part covered the design and technical solution for transformer condition monitoring. Also verification is included shortly. The basis for the pilot project design was requirements. Pilot project evaluates the condition monitoring framework and measurement devices like temperature, moisture and dissolved gas analysis device. The condition monitoring framework is integrated to secondary system. Measurement devices have some overlap but this is done by purpose. This way it is possible to gather more information about different measurement points and afterwards decide which the best options are.

As a conclusion it can be said that there is a need for transformer condition monitoring. There is plenty of experience from off-line monitoring and also from on-line monitoring. Automated condition monitoring on the other hand is taking its first steps. There is already good variation of devices but overall solution with decent costs is still missing. Also communication between different devices is very limited. One major challenge is lack of standard and this will also slow down the development of measurement devices.

The main result from this thesis is that framework for transformer condition monitoring is needed and it must be decently priced. The proposed solution is integrating framework to secondary system products like protection relays and station automation

devices. The thesis also presents a possible solution for a pilot project to start taking ideas into real solutions.

During the research it became clear that the transformer condition monitoring has many dimensions and everything can't be covered in one thesis. Based on this thesis next research topics could be for example detailed comparison of different monitoring methods, considering economic effects of monitoring system and detailed specification for the monitoring framework.

Thomas A. Edison once said "The value of an idea lies in the using of it." This is the key element what was also mentioned during the interviews and the message was that perfect transformer monitoring system is impossible to design on paper so hard work is needed to see if ideas work in real world.

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APPENDIXES

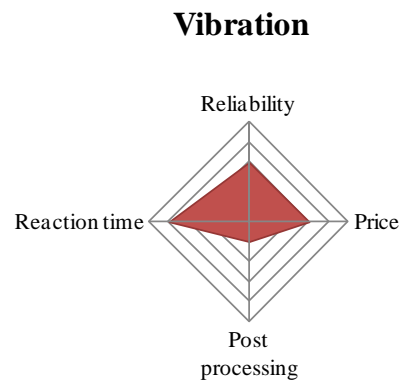
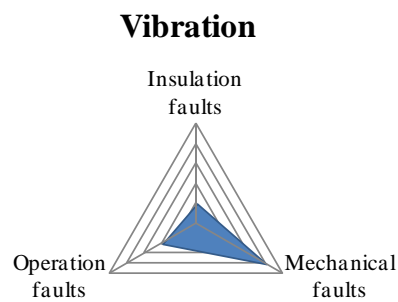
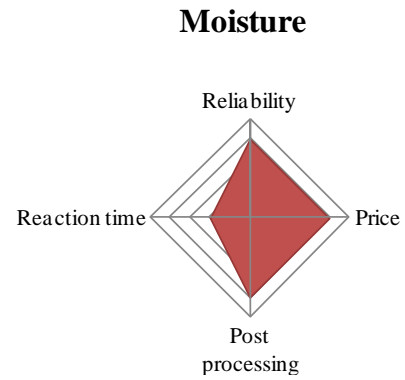
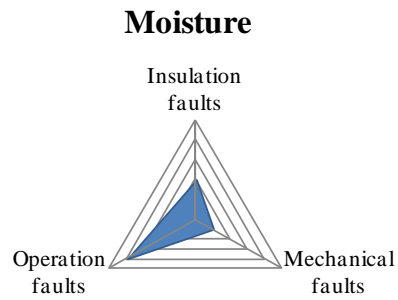
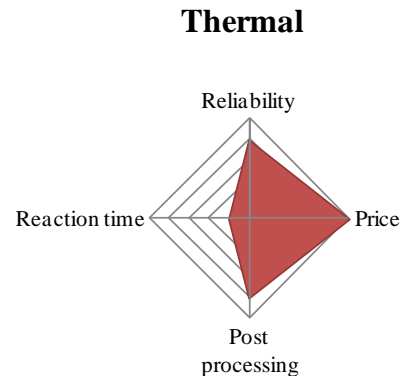
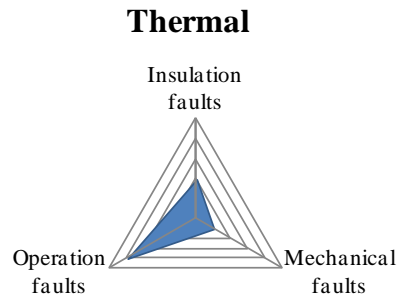
APPENDIX 1. Cause and effects

Asset type	Natural aging processes	Factors which accelerate aging	Natural outcome if left unchecked	On-line monitoring signature to watch for	Note
Transformers (tank & core)	paper cellulose decomposes to CO, CO ₂ , H ₂ O, acids, & glucose (which further breaks down into furans)	water ingress from outside, internal water from paper, heat, oxygen & continuing presence of acids	continuous degradation of paper insulation component	water (H ₂ O) acids	1
	oil decomposition into various gases	partial discharge (corona) (<300°C)	localised cumulative insulation damage and eventual failure	hydrogen (H ₂) partial discharge RF currents; acoustic detection	
		thermal fault (>300°C and <700°C)	high localised stress on oil, paper and bus work leading to damaged components & functional failure	hydrogen (H ₂), methane (CH ₄), ethane (C ₂ H ₆), ethylene (C ₂ H ₄)	
		arcing fault (>700°C)	rapid decomposition of oil and paper into gases, explosion likely if not stopped quickly	hydrogen (H ₂), acetylene (C ₂ H ₂)	
On-Load Tap Changers	electrical current flows	accumulated water dissolved in oil	oil will saturate and become free when due point reached	% water (H ₂ O) dissolved in oil low oil temperature range	
		excessive heat in core due to elevated load currents	very rapid breakdown of insulation papers in core	core temperature monitoring	2
		short circuit fault currents	core distortion, paper damage and loss of clamping pressure	frequency response analysis (FRA)	3
		drive mechanism sticky or erratic in operation	high wear and eventual drive mechanism failure	drive motor rotor current vibration monitoring acoustic monitoring	
	breakdown of insulation system	drive mechanism totally jams (locked rotor)	no secondary voltage control with likely damage to drive motor	drive motor rotor current	
	damage to mechanism	stops over correct tap contact but with insufficient contact pressure	gradual heating of tap changer oil and cumulative damage to contact	slower increase in OLTC temperature (wrt. main tank temperature) when remaining on this tap setting for longer periods	
	wear of mechanical components	stops between two adjacent tap positions	rapid heating of tap changer oil due to series resistor remaining in circuit continuously	faster increase in OLTC temperature (wrt. main tank temperature) with heating rate dependent on load current	
		low oil level leading to arcing fault	serious damage or explosion	header tank oil level	

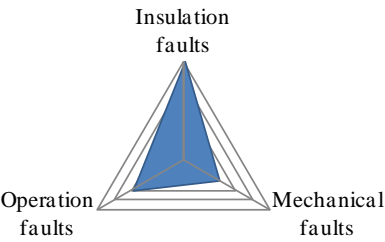
Asset type	Natural aging processes	Factors which accelerate aging	Natural outcome if left unchecked	On-line monitoring signature to trend	Note
Bushings & CTs	damage to porcelain	rapid temperature swings or extreme environmental conditions; conductive oil by-products build up on porcelain inside walls	crazing allowing dirt build-up and water ingress with reduction of insulation properties;	changes in tan ("tan delta")	
	core paper deterioration	elevated operating temps; oil leak leading to papers drying out and cracking	localised partial discharge promoting further paper (and oil) deterioration (runaway condition)	partial discharge RF currents changes in tan	
	oil deterioration	similar mechanism as within transformers	localised partial discharge promoting further oil (and paper) deterioration (runaway condition)	partial discharge RF currents changes in tan	5
	short circuits between foil layers	design/manufacturing defects; paper / oil aging; conductive ink migration	higher capacitance leading to increased capacitive current	increase in bushing C1 (and possibly C2) capacitance	4
	small voids within insulation system	partial discharge (corona) caused by tiny flashovers inside voids in insulation	localise insulation damage with formation of carbon and/or shorts between foil layers	partial discharge RF currents changes in tan	
	large temperature variations	differing coefficient of expansion of bushing components; rapid cooling can create bubbles in oil	frequent thermal cycling results in excessive seal wear in turn leading to oil leak and/or water ingress; also end paper damage & possible corrosion in tap chamber	usually will show up as an increase in tan and/or partial discharge RF currents; tan becomes sensitive to temperature	6
Switchgear	contact wear	excessive interrupting duty; higher operation count	cumulative damage which can lead to catastrophic failure thru failure to clear fault arc in time	accumulated I ² t duty of main contact; arc duration	
	dielectric compromise	partial discharge; contaminated oil; worn baffles; nozzle ablation	result in longer arc clearance times gradually increases to compromise breaker failure time	partial discharge RF currents arc duration; arc restrike count & duration; acoustic (ultra sonic)	
	mechanism problems	higher operations count; "stiff" or dry linkages; worn or faulty latches; pneumatic/hydraulic faults	gradual (degradation) or sudden failure of breaker	interval between trip command (or "a" contact opening) and "b" contact closing	7
	control circuit failure	shorted or open trip coils; shorted or open external circuits; terminal contact problems; trip relay status	corrosion or gradual wear leading to insulation breakdown (short) or wire fatigue (open). Either way, trip circuit will malfunction.	self-monitoring tripping relay; healthy trip circuit	8

APPENDIX 2.

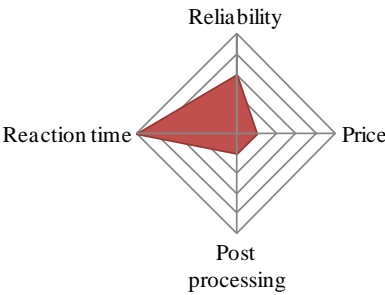
Radar charts for monitoring method evaluation



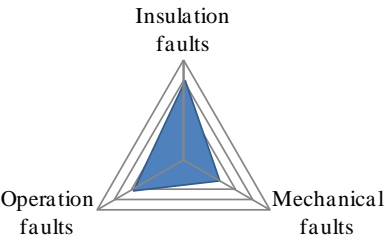
Partial discharge



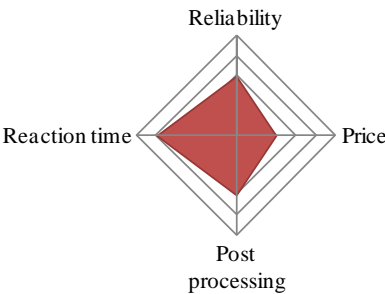
Partial discharge



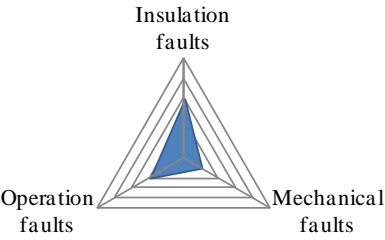
DGA (Multi-gas)



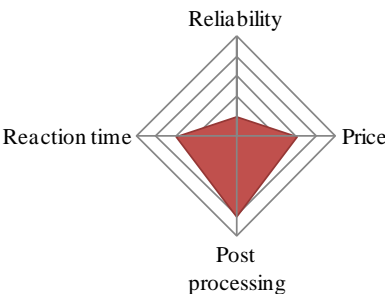
DGA (Multi-gas)



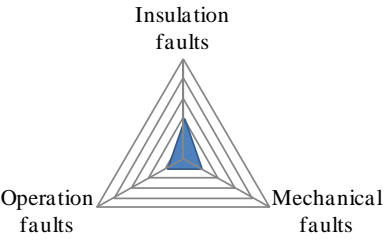
DGA (Combustible gasses)



DGA (Combustible gasses)



Tan delta



Tan delta

